ASSESSING OPPORTUNITIES TO INCREASE GLOBAL FOOD PRODUCTION WITHIN THE SAFE OPERATING SPACE FOR HUMAN FRESHWATER USE

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Abstract

Agriculture is today's most important driver of ecosystem degradation and critical impairments of Earth system functioning. To maintain life-supporting ecosystems for long-term human prosperity, the Sustainable Development Goals (SDGs) now commit all countries to a transformative agenda to shift agriculture toward environmental sustainability, joined with the doubling of productivity to eradicate hunger by 2030. However, there is little quantitative knowledge on how to attain this historic twin-challenge. In this thesis, I assess planetary opportunities in agricultural water management interventions to reconcile future food production with environmental limits to freshwater use. I explore solution-oriented ways to improve on-farm water management in rainfed and irrigation systems alike, while safeguarding environmental flows (EFRs) to protect riverine ecosystems. To study possibilities, challenges, and interactions of different water management pathways, I advanced a state-of-the-art global modeling framework that enables to quantitatively address such questions based on detailed, mechanistic, and spatially and temporally explicit representation of underlying biophysical processes and their feedbacks to management interventions. Four research papers / thesis chapters provide the evidence for the following main findings. First, a systematic upscaling of EFRs to global coverage indicates that 39% of current freshwater withdrawals for irrigation are unsustainable and occur at the cost of ecosystems. Second, the aggregate of these local water overdrafts suggests that the planetary boundary for human freshwater use might be notably lower (2800 vs. 4000 km^3/yr) than previously estimated. Third, implementing policies to safeguard EFRs worldwide would significantly affect agriculture, cutting irrigated food production by 14%, with a >20% total kcal loss across irrigation hotspots. Fourth, as the main result and synthesis of management interventions, improving irrigation systems in combination with optimizing the use of precipitation water on a broad basis, provides effective and accessible measures to compensate for adverse impacts from protecting EFRs and climate change. When implemented, such integrated farm water management interventions could sustainably intensify global food production (+40% kcal) to the degree sufficient to halve the global food gap for a growing world population by 2050. In conclusion, this thesis provides the first comprehensive and systematic assessment of hitherto largely unquantified global opportunities in sustainable intensification of agriculture regarding farm water management, yet within the safe operating space for human freshwater use. While requiring corroboration by finer-scale research, the innovative quantitative foundation provided in this thesis suggests that farm water management merits a rise in political attention, and it can inform a more comprehensive discussion of related SDG targets and their interaction.

Contents

Abstract iii

Contents vii

List of Figures x

List of Tables xi

Abbreviations xiii

1. Introduction 1

1.1. A challenge for human ingenuity . . . 2

1.1.1. Conundrums of settled life . . . 2

1.1.2. Growing societies in face of environmental limits . . . 4

1.1.3. The twin-challenge: people and planet . . . 7

1.1.4. Planetary opportunities in sustainable intensification . . . 10

1.2. Water as key factor: between scarcity and optimism . . . 11

1.2.1. Irrigated farming — ratchet and hatchet . . . 12

1.2.2. Rainfed agriculture — the crux of a new Green Revolution . . . 17

1.3. Methodological rationale . . . 19

1.4. Research outline . . . 21

2. Water savings potentials of irrigation systems 25

2.1. Abstract . . . 26

2.2. Introduction . . . 26

2.3. Methodology . . . 30

2.3.1. Definition of irrigation efficiency . . . 30

2.3.2. Suitability of the dynamic process model LPJmL to simulate irrigation systems 31

2.3.3. Implementation of the new irrigation scheme in LPJmL . . . 33

2.3.4. Development of new input data set for grid-level irrigation system distribution 37

2.3.5. Simulation protocol . . . 38

2.4. Results . . . 39

2.4.1. Global patterns of irrigation efficiency . . . 39

2.4.2. Global irrigation water fluxes . . . 40

2.4.3. Potential of irrigation system transitions 41
2.4.4. Evaluation of simulation results 44
2.5. Discussion 47
2.5.1. Significance of results 47
2.5.2. Modeling issues 48
2.5.3. On irrigation system transitions 50
2.6. Conclusions 51
2.7. Author contribution 52
2.8. Acknowledgements 52

3. Toward a revised planetary boundary for consumptive freshwater use 53
3.1. Abstract 54
3.2. Introduction 54
3.3. Ecosystems set boundaries for human water appropriation 55
3.4. Quantitative assessment of EFRs and respective revision of PB-Water 56
3.5. Land use and climate change effects on the freshwater boundary 60
3.6. Staying within interlinked water and land boundaries 62
3.7. Conclusions 63
3.8. Acknowledgements 65

4. Reconciling irrigated food production with environmental flows in face of SDG implementation 67
4.1. Abstract 68
4.2. Introduction 68
4.3. Results 70
4.4. Discussion 75

5. Integrated crop water management might sustainably halve the global food gap 79
5.1. Abstract 80
5.2. Introduction 80
5.3. Methods 84
5.3.1. Simulation of water management interventions 84
5.3.2. LPJmL model 88
5.3.3. Simulation protocol 89
5.4. Results 90
5.4.1. Effects of integrated water management on crop production, transpiration coefficient, and the water gap 90
5.4.2. Water savings potentials of irrigation systems 93
5.4.3. Irrigation expansion with saved irrigation losses 93
5.4.4. Effects of soil moisture conservation and water harvesting on rainfed systems 94
5.4.5. Climate change impact 95

5.4.6. Evaluation of results and modeling issues 96
5.5. Discussion 99
5.6. Conclusion 101
5.7. Acknowledgements 101

6. Synthesis **103**
6.1. Achievements 104
6.1.1. Methodological achievements toward the quantification of planetary opportunities in farm water management 104
6.1.2. Answers to the research questions 105
6.2. Discussion 107
6.2.1. Significance of the results 107
6.2.2. Co-benefits of water management and barriers to implementation 114
6.2.3. Closing the food gap within PB-Water and PB-Land: further simulations . 118
6.2.4. Research outlook 122
6.3. Conclusions 125
6.3.1. Summary 125
6.3.2. Potential implications 126

A. Supplementary Information for Chapter 2 **131**
A.1. Water balance equations 131
A.2. Development of a new input for spatially explicit distribution of irrigation systems 132
A.3. Supplementary figures 140

B. Supplementary Information for Chapter 4 **145**
B.1. Supplementary tables and figures 145
B.2. Methods 150
B.2.1. Environmental flow requirement objectives 150
B.2.2. Illustration of pressure on the freshwater boundary. 152
B.2.3. Model and simulation protocol 152
B.2.4. Model validation 153

C. Supplementary Information for Chapter 5 **157**
C.1. Supplementary tables and figures 157

Bibliography **165**

Acknowledgements **195**

List of Figures

1.1. Historical land-use transitions . . . 4
1.2. Evolution of global irrigation area and water withdrawals . . . 5
1.3. The grand challenge: sustainable development within the safe, and toward the just operating space . . . 8
1.4. Water saving potentials of low-yielding green water systems . . . 17
1.5. Outline and linkings of research studies . . . 21

2.1. Pathways of irrigation water fluxes . . . 28
2.2. Irrigation water flows in LPJmL . . . 35
2.3. Global distribution of irrigation systems at country level . . . 39
2.4. Global patterns of beneficial irrigation efficiency . . . 40
2.5. Global patterns of beneficial irrigation efficiency for each irrigation system . . . 42
2.6. Decomposition of beneficial and non-beneficial irrigation water fluxes for each simulated CFT and irrigation system . . . 44
2.7. Global patterns of potential changes in water productivity and non-beneficial consumption . . . 45
2.8. Relation of blue water consumption and blue water transpiration . . . 48

3.1. Simulated river discharge and environmental flow estimates . . . 58

4.1. Severe hydrologic alterations at selected river stretches . . . 71
4.2. Governing environmental flows affects food production . . . 73
4.3. EFR constraints on country-level kcal production under current and improved irrigation 74
4.4. Evaluation of LPJmL-simulated key variables . . . 76

5.1. Hydro-climatic opportunities in crop water management . . . 82
5.2. Global distribution of the water gap . . . 84
5.3. Planetary opportunities in crop water management . . . 91
5.4. Water management bridges the rainfed water gap and cuts irrigation water use . . . 92
5.5. Planetary opportunities in blue water management . . . 94
5.6. Planetary opportunities in green water management . . . 95
5.7. Water management buffers adverse climate change impacts . . . 97

6.1. Improved water management relieves pressure from the planetary boundaries . . . 119

6.2. A vision for closing the global food gap 121

A.1. Parameter sensitivity analysis for the distribution uniformity scalar 140
A.2. Global patterns of beneficial irrigation efficiency 140
A.3. Sensitivity analysis for the irrigation threshold parameter 141
A.4. Dependencies of non-beneficial irrigation water fluxes on its main biophysical driving factors 142
A.5. LPJmL river routing 143

B.1. Uncertainty range of the current status of environmental flow transgressions 145
B.2. Current status of environmental flow transgressions in absolute terms 146
B.3. Integrated water management overcompensates EFR effects on kcal production globally 148
B.4. EFR constraints on country-level kcal production under integrated water management 148
B.5. Evaluation of observed and LPJmL-simulated yield variability 155

C.1. World map of transpiration coefficients 157
C.2. Sensitivity analysis of irrigation parameters 158
C.3. Sensitivity analysis of supplemental irrigation 158
C.4. Water trade-offs associated with water harvesting 159
C.5. Water management buffers adverse climate change impacts — constant CO_2 . . . 160
C.6. Water management buffers adverse climate change impacts — transient CO_2 . . . 161

List of Tables

2.1. Parameterization of irrigation systems in LPJmL 35
2.2. Irrigation system suitability by crop type 37
2.3. Total annual sums of irrigation water fluxes 41
2.4. Global water saving and water productivity potentials with irrigation transitions . 43
2.5. Evaluation of simulated irrigation efficiencies 47

3.1. Calculation of the planetary boundary for freshwater 61

4.1. Agricultural impacts under different irrigation and flow conservation scenarios. . . 70

5.1. Portfolio of water management interventions simulated in this study. 85
5.2. Overview of model simulations 87
5.3. Irrigation expansion potential with water savings 90
5.4. Water management buffers adverse climate change impacts 96

6.1. Future food gap puts pressure on planetary boundaries 120

A.1. Irrigation system shares by country 134

B.1. Global sums of food production and water abstractions for different management scenarios 147
B.2. Country-level aggregation of changes in kcal production under EFR constraints and irrigation improvements 149
B.3. Definition of hydrological seasons and respective EFR allocations 151

C.1. CMIP5 model and group names used in this study 162
C.2. Selection of reference studies for water management interventions 162

Abbreviations

AD	Anno Domini, number of years since the birth of Jesus Christ
AEI	Area Equipped for Irrigation
AF	Mean annual river Flow
AR	Irrigation Application Requirements
AQUASTAT	FAO's global water information system
BP	Before Present, number of years before 1950 AD
BW	Blue Water
cap	Capita
cf.	Compare, or see also
CFT	Crop Functional Type
CMIP5	Climate Model Intercomparison Project phase 5
CRU	Climate Research Unit
CWP	Crop Water Productivity
d	Day
D	Atmospheric water demand
DGVM	Dynamic Global Vegetation Model
Dr	Drainage or deep percolation
E	Soil evaporation
EFR	Environmental Flow Requirements
FAO	Food and Agriculture Organization of the United Nations
FAOSTAT	FAO Statistics Division
FPU	Food Production Unit
GCM	Global Climate Model
GDP	Gross Development Product
GIR	Gross Irrigation Requirements
GPCC	Global Precipitation Climatology Centre
GRDC	Global Runoff Data Centre
HIL	Water use for Household, Industry, and Livestock
I	Interception loss
ICID	International Commission on Irrigation and Drainage
IWC	Irrigation water consumption
IWD	Irrigation water withdrawal
IWRM	Integrated Water Resources Management
l	Liter
LAI	Leaf Area Index
kcal	Kilocalorie
LPJmL	Lund–Potsdam–Jena with managed Land model
MDGs	Millennium Development Goals
MENA	Middle East and North Africa
MF	Mean monthly river Flow
MIRCA2000	Monthly Irrigated and Rainfed Crop Areas around the year 2000
NIR	Net Irrigation Requirements
PBs	Planetary Boundaries
PB-Water	Planetary Boundary for human freshwater use
PET	Potential Evapotranspiration
PFT	Plant Functional Type
PIK	Potsdam Institute for Climate Impact Research
R	Surface and subsurface runoff
RCP	Representative Concentration Pathway
RNC	Ratio of Non-beneficial Consumption

S	Soil water Supply
SDGs	Sustainable Development Goals
SMC	Soil Moisture Conservation
SSA	Sub–Saharan Africa
T	Transpiration
TC	Transpiration Coefficient
UN	United Nations
VMF	Variable Monthly Flow method
WH	Water Harvesting
WH_{ex}	*ex situ* Water Harvesting
WH_{in}	*in situ* Water Harvesting
WHC	Water Holding Capacity
W_{bc}	Beneficial Water consumption
W_{nbc}	Non-beneficial Water consumption
yr	Year

Chapter 1.

Introduction

Societal commitments to a sustainable future put agricultural systems under a heavy strain. The century-old quandary to provide ever-growing human populations with sufficient food takes on a new dimension, as it now becomes apparent that human development is grounded in environmentally sound agriculture. However, the transformation of global farming to sustainable forms remains unattainable without a revolution of agricultural water use, because tightening freshwater resources both constrain food security and drive environmental degradation. In this thesis I quantitatively explore worldwide opportunities in agricultural water management to meet future food requirements in the light of the Sustainable Development Goals. The focus is on the potential contribution of improved on-farm water management allied with the attaining of sustainable withdrawals to safeguard riverine ecosystems. To highlight challenges toward sustainable food security in the 21st century, this introduction provides a historical background of the escalating pressures on agriculture and freshwater resources alike. Thereafter, I present a description of the methods used, and my research outline is subsequently formulated in Section 1.4.

1.1. A challenge for human ingenuity

1.1.1. Conundrums of settled life

Agriculture is the foundation of all cultures[1]. The defining characteristic of human rise are two major transitions, the Neolithic revolution (10,000 – 5,000 yr BP) and the Industrial Revolution (1700 – 2000 yr AD) (Schellnhuber 2015). Through the prehistoric shift from foraging to farming — humans learned to domesticate plants and animals for food, livestock as a labor substitute, and invented storage — humanity tipped the comparative advantage[2] and entered Neolithic times, which sustained larger human populations and might form the largest historical step-up in human culture (Grigg 1974; Diamond 2002). Thereby freed up human capital was the cornerstone of sedentism and sophisticated social systems (nation states, markets, advanced communication), which was key to early cities (Weisdorf 2005). Since its very beginning, quandaries in food availability have characterized human development. But with the capacity of social learning and knowledge built across generations, human societies have implemented — first by chance or trial and error — a long series of ingenious achievements to nourish their ever-increasing populations (Henrich and McElreath 2003; De Fries et al. 2012). Maintaining soil fertility (e.g. through human manure, and later guano, and ground animal bones), introducing new crops (e.g. the potato's ascent as a staple in Europe), and the ancient trick to defeat water limitation (rainwater harvesting and irrigation systems) set the scene for the race between food production increase and population growth: human populations grew to 900 million by 1800 (Grigg 1974; Postel 1999; Ellis 2011). Therewith, mankind has settled down and the question changed from how much space a given number of people need for self sufficiency — in Paleolithic times people hunted and gathered over vast areas — to how many people can live off a given piece of land (Schellnhuber 2015).

The second major agricultural upswing occurred in the course of the industrialization of England, ignited around 1800 and spreading quickly around the world. Pivotal innovations in technology such as an improved version of the Chinese iron plough and the seed drill, paired with land enclosure and new crop rotation systems, increased agricultural production dramatically and are seen as a cause of the Industrial Revolution across sectors (Thomas 2005; DeFries 2014). Subsequently,

[1] As a distinguishing aspect of humanity, the UNESCO (2002) regards culture (Latin "cultura" — "to cultivate") as "the set of distinctive spiritual, material, intellectual and emotional features of society or a social group. It encompasses [...] lifestyles, ways of living together, value systems, traditions and beliefs".

[2] There is scientific consensus on the timing and geographic locations of the origins of human farming, but the question "why farm?", i.e. identifying the attractor that explains satisfactorily why human societies took the step from foraging to farming, is still subject to debate (Diamond 2002; Weisdorf 2005; DeFries 2014).

the industrial fixation of inorganic nitrogen (proliferation of the Haber-Bosch process), and the replacement of human and animal labor with fossil fuel, accompanied by major increases in life expectancy, fueled a population explosion and far-reaching demographic upheaval. By the mid of the 19th century only 20% of the population employed in the agricultural sector could free 80% of human capital to forge ahead with other sectors (Grigg 1974).

Although populations doubled over the past 50 years, to now almost 7.5 billion (Population Reference Bureau 2016), the latest "pivot" (DeFries 2014) of agricultural industrialization — the Green Revolution — was capable of tripling stable crop production with only a 30% increase in cultivated land area (FAO 2002; Pingali 2012). Propelled by Norman Borlaug, a large-scale program of plant breeding (high-yielding varieties such as hybrid corn and dwarf wheat, but also shortening of growing period), modern agricultural systems (mechanization and rigorous application of chemical fertilizer), and above all, the systematic expansion of irrigation, improved especially wheat yields significantly (DeFries 2014). From Mexico spreading to Pakistan, India, and other countries, food security[3] greatly improved and millions of people were saved from starvation, most notably in the developing world. The amount of food produced surpassed the amount required for each person and resulting decreased prices dramatically improved energy and protein consumption, much for the poor, but even at global scale from 2200 $kcal\ cap^{-1}d^{-1}$ in 1960 to 2700 $kcal\ cap^{-1}d^{-1}$ in 2000 (IFPRI 2010). This success rests upon concerted investments in agronomic research, infrastructure, and market development, but most importantly, it would not have been realized without large-scale water appropriations for irrigation from new and often nonrenewable sources (Postel 1999; Cassman and Grassini 2013).

The above illustrated pivots provide an account of the ever-expanding quest to feed human populations and to provide therefore required freshwater resources. But the remarkable ascent did not come without repeated devastating setbacks. Settled life, dense populations, and stratified societies gave rise to crowd diseases, conflicts, and famines (Diamond 2002). For instance, during Ireland's Great Famine in the 1840s potato blight attacks ravaged the nationwide dependency on a single potato variety — Ireland's population fell by 25% (Curran and Fröling 2010). In the long run, though, mankind developed solutions and proved successful to stretch continuously the number of people to survive. However, it is not all that clear whether we can rely on that trend to be continued throughout future challenges. The question if human ingenuity will proceed to

[3] "A situation that exists when all people, at all times, have physical, social and economic access to sufficient, safe and nutritious food that meets their dietary needs and food preferences for an active and healthy life." (FAO et al. 2015)

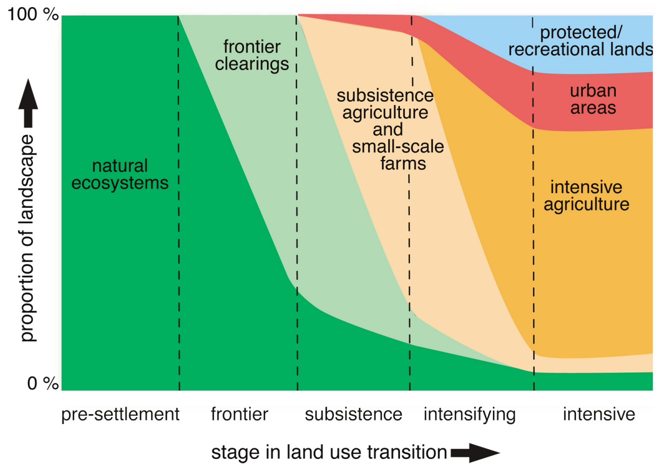

Figure 1.1.: Historical land-use transitions. This illustration outlines historical stages in transition of the terrestrial biosphere (source: Foley et al. (2005)).

circumvent looming quandaries in the tightening water-food nexus toward future food security fuels a long running dispute.

1.1.2. Growing societies in face of environmental limits

The bottleneck of planetary finite resources has been recognized already by Thomas R. Malthus in the late 18th century, who predicted catastrophic side effects with humanity's expansion (Malthus 1798). Since then the paradigm of supposedly inevitable "limits to growth" fostered prominent support (e.g. Meadows et al. 1972; Ehrlich 1968). This worldview is contested by Julian Simon, the classic protagonist of the theory that technological and social progress will not only continue to stretch food abundance, but make it infinite — the ultimate resource is therefore not oil or water, but human ingenuity (Simon 1981; Ruttan 1971). Both beliefs, however, prove incapable of describing historical broader perspectives. The Neo-Malthusian (Aligica 2009) score of dire predictions of famine underestimate the ability of human societies to adapt and change and thus overcome chronic food deficiencies as demonstrated by the actual course of history — Julian Simon won on the bet against Paul Ehrlich (Sabin 2013). But Simon's complacent idea that people are resource creators, not destroyers, neglects already profound and potentially irreversible human alterations of Earth-system functioning (Reid et al. 2005).

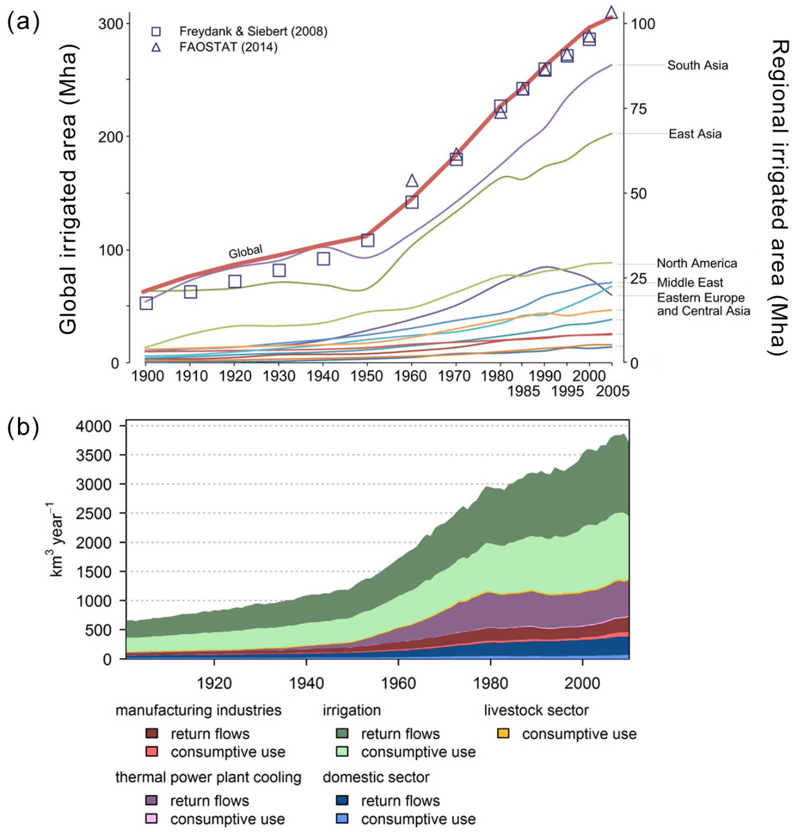

Figure 1.2.: Evolution of global irrigation area and water withdrawals. Chart **(a)** illustrates the evolution of global and regional area equipped for irrigation (AEI, in Mha) for the 20th century (adapted from Siebert et al. (2015)). Chart **(b)** highlights resulting global water withdrawals for irrigation and other water use sectors (source: Müller Schmied et al. (2016)).

In quest of the need to provide food, anthropogenic forces transformed the terrestrial biosphere (Figure 1.1), from mostly natural landscapes to predominantly anthropogenic biomes[4] (Ellis et al. 2010), which has critical impacts on the diversity, composition, and life-supporting functioning of the remaining natural ecosystems, and contributes to climate change (e.g. Tilman 1999; Foley et al. 2005; Barnosky et al. 2011; Hartmann et al. 2013). Although the Green Revolution-driven intensification held back more extensive land conversion to agriculture[5], it came at the cost of profound environmental consequences (Pingali and Rosegrant 1994). Monocultures accompanied with chemical fights against evolving pests and diseases impair biodiversity and human health

[4]By 2000 39% of ice-free land surface have turned into agricultural land or settlement, only 25% remain natural, with distinct geographical disparities.

[5]Recent estimates suggest an even smaller extent than previously claimed (Stevenson et al. 2013).

(Eddleston et al. 2002). More synthetic fertilizer is applied in agriculture than is fixed naturally in all terrestrial ecosystems, with widespread effects on water quality and coastal and freshwater ecosystems (Smil 1991; Galloway and Cowling 2002). Among the most pervasive factors, freshwater depletion, dam construction, and river diversion — in the first place to quench the thirst of irrigation (Figure 1.2) — have transformed the hydrologic cycle of the Earth to the degree that approximately 25% of the world's major rivers no longer reach the ocean (Gleick 2003; Molden 2007). The extent of the world's wetlands has collapsed to one third (Ramsar Convention 2015), and half of all accessible freshwater is used for human needs (Postel et al. 1996; Vörösmarty et al. 2005).

The industrialization expanded the human imprint on the planet, while agricultural intensification through ever-increasing resource use became the most important local to global driver of critical influences on Earth-system processes (Matson 1997; Foley et al. 2005; Reid et al. 2005; IAASTD 2009). The arising anthropogenic domination over nature manifested itself through the remarkable crescendo of the human enterprise in a multitude of aspects — the Great Acceleration (Steffen et al. 2007). This grounds proposals that the Earth System has entered a new geologic epoch, the Anthropocene, the era of mankind's massive impact on Earth-system functioning (Crutzen 2002; Monastersky 2015; Steffen et al. 2016).

The Holocene provides a stable and largely benign environment for humanity to thrive. But the use of natural resources is now so extensive that the risk increases to push the Earth system into a post-Holocene state with characteristics that potentially undermine system resilience[6] (e.g. the capacity to buffer environmental shocks such as droughts and floods), and human well-being. Such risks have been acknowledged by defining critical environmental limits to anthropogenic influences on the Earth system (e.g. Petschel-Held et al. 1999; Lenton et al. 2008), formulated later as "planetary boundaries" (Rockström et al. 2009c; Steffen et al. 2015). As a precautionary principle, the nine planetary boundaries — absolute biophysical thresholds or limits — delineate the safe operating space for humanity, and thus sustainable long-term prosperity (see Steffen et al. (2015) for details). Although such numbers are difficult to quantify and to some degree still lack conceptional scrutiny, they mark actionable targets already and thereby move into policy space — providing a tool for planetary stewardship. Despite a line of critical discussions (see Section 6.2.4), there is strong evidence that the boundaries for land use, biosphere integrity, nitrogen and phosphorus flows,

[6]The term resilience was originally introduced into the field of ecology by Holling (1973) as the capacity of an ecological system to respond to a perturbation or disturbance by resisting damage and recovering quickly. But a broader understanding of the capacity to adapt and transform for persistence of alternative stable states (Folke et al. 2010) led to a popular definition by Walker et al. (2004): "Resilience is the capacity of a system to absorb disturbance and reorganize while undergoing change so as to still retain essentially the same function, structure, identity, and feedbacks". Hereinafter I refer to this definition.

and climate change are breached already at global level. The freshwater boundary, as a critical concern for global food production, is not yet transgressed at global level, but in many regions (detailed in Section 1.2.1). The planetary boundary concept suggests accordingly that there is only marginal room left for additional agricultural expansion and conventional intensification (based on higher inputs of land, fertilizer, and water). In turn, in regions with e.g. water over-exploitation, such transgressions of environmental limits must be reset to maintain future capacities for human development (Steffen et al. 2015).

This appears particularly relevant in view of the fact that not all countries benefited equally from historic agricultural intensifications. Today, severe gaps in human deprivation need to be bridged. More than 2 billion people are affected by water stress, which hinders economic and social development (ECOSOC 2016a). Mainly as a result of vulnerable and low-yielding farming systems, 800 million people remain chronically undernourished[7], 160 million children suffer stunted growth, and >10% of the world's population still live in extreme poverty (<US$1.90 $cap^{-1}d^{-1}$) (FAO et al. 2015; ECOSOC 2016a). Such realities underline that agriculture is still at the center of sustainable development[8], even though it is clear that tackling hunger and malnutrition[9] is not only about the amount of food produced.

1.1.3. The twin-challenge: people and planet

With the recognition of environmental limits, notions of prosperity change; away from resource dependency toward more sustainable ways of well-being (Tibbs 2011; Raworth 2012b). But sustainable development in the Anthropocene takes more than environmental sustainability. Equally important are social and economic foundations (Griggs et al. 2013). Kate Raworth (2012a) acknowledged the need to add such social boundaries for human development to the planetary boundary concept, which would create a non-trivial subspace, the "safe and just space for humanity". The right to food therefore depends on environmental integrity (World Social Science Report 2016), which forms one dimension of the just space, and is in turn delineated by the planetary boundaries. For illustration,

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[7] From a total 795, 780 in developing countries: 233 in Africa, 512 in Asia, 34 in Latin America and the Caribbean, 1 in Oceania (in million) (FAO et al. 2015).

[8] Sustainable development in the Anthropocene is defined herein as: "Development that meets the needs of the present while safeguarding Earth's life-support system, on which the welfare of current and future generations depends"(Brundtland Commission 1987; Griggs et al. 2013).

[9] The term "hunger" is used herein synonymously with undernourishment. Malnutrition includes undernutrition, overnutrition, and micronutrient deficiencies (FAO et al. 2015).

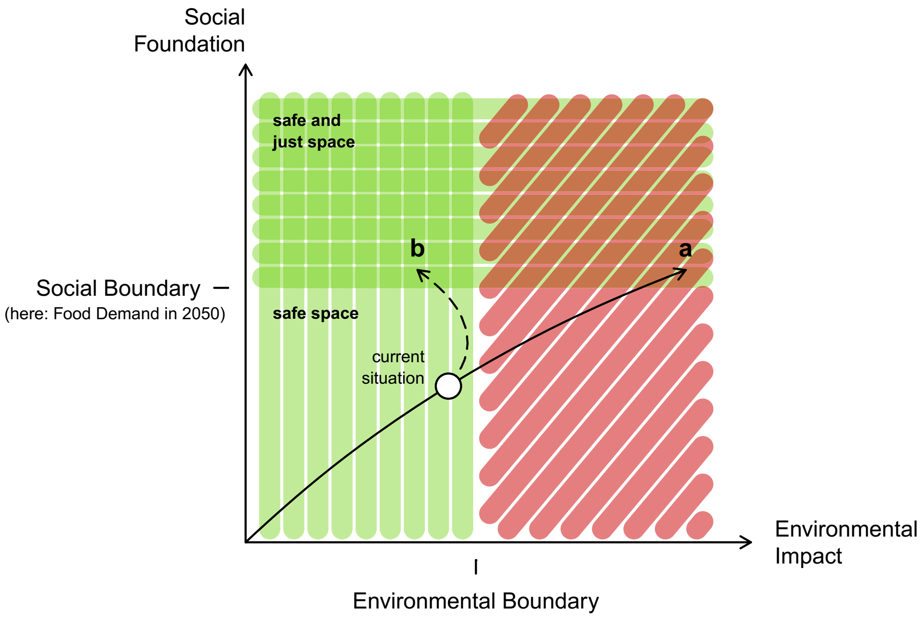

Figure 1.3.: The grand challenge: sustainable development within the safe, and toward the just operating space. This conceptual illustration outlines two agricultural intensification pathways across the space delineated by environmental impact and social deprivation. Pathway **(a)** highlights conventional resource-based intensification that transgresses the environmental boundary to meet the global food target. Pathway **(b)** draws an example of sustainable development within the safe operating space. The environmental boundary exemplarily stands for critical levels of Earth system processes such as freshwater use. The social boundary marks the threshold of an agreed social foundation and thereby separates the safe and just operating space. Here, the social boundary is represented by food demand in 2050.

Figure 1.3 simplifies the safe and just space between food production and the planetary boundary for freshwater use, and thereby provides the conceptual framing for this thesis.

In the vein of integrating social needs and environmental limits, a set of Sustainable Development Goals (SDGs) was formulated and agreed on by the United Nations in September 2015 (United Nations 2015a). The 2030 Agenda for Sustainable Development[10] — relevant to developed and developing nations alike — is a transformative and ambitious global vision for sustainability, eradication

[10]The official framing of the SDG agenda.

of hunger, and poverty. As a follow-up of the partly successful Millennium Development Goals[11], they now focus more prominently on environmental integrity, integrating the three dimensions of sustainable development: nested environmental, social, and economic sustainability, based on closely interwoven goals and targets[12]. This new direction — integrating people and the planet — is an important step forward as the SDGs now acknowledge that food, livelihoods and natural resource management can no longer be looked at separately (FAO 2016). They stipulate a sustainable and resilient food production system (target 2.4) and sustainable withdrawals (target 6.4) as agreed goals among all nations. On the same page, however, target 2.3 aims at doubling both agricultural productivity and incomes of smallholder farmers[13] by 2030, in support of target 2.1, i.e. hunger eradication and food security. This lays out a bold and seemingly conflicting agenda. Although there was great effort in providing an indicator framework for progress monitoring (ECOSOC 2016b), many of the SDG targets and related indicators are insufficiently defined, or not backed by available data. To that end, there were proposals to integrate the planetary boundary concept into the SDGs framework, as they provide viable and actionable thresholds to be linked to SDG targets (Griggs et al. 2014). But the General Assembly did not stipulate such and agreed environment-related targets and indicators mainly remain vague (ECOSOC 2016b).

The strong rise in the human population is likely not to level off until 2050, by which time it is expected to have reached 9–10 billion (United Nations 2015c; UNFPA 2013). The unprecedented confluence of socio-economic global mega-trends such as economic growth and urbanization lead to substantial changes in consumption patterns and more varied, high-quality diets and thus resource requirements. This results in suggestions that crop calorie production needs to be increased by 60-100% in the forthcoming decades to eradicate hunger (IAASTD 2009; Alexandratos and Bruinsma 2012; Valin et al. 2014). Competition for water, land, and energy will intensify, which further complicates the challenge of closing the global food gap[14] and will test the resilience of local to global food systems (Godfray et al. 2010; Foley et al. 2011; Searchinger et al. 2013; Foresight 2011). The current slowing down of historic yield increases (Ray et al. 2012) is expected to face adverse impacts through unabated climate change, which is likely to exacerbate food insecurity particularly among the poorest by increasing water stress and hydro-climatic variability (Lobell

[11] The target of global poverty reduction was reached five years ahead of schedule, yet more than a billion people still live in extreme poverty today. Shortfalls remain in achieving the targets related to food security (United Nations 2016b).

[12] 17 aspirational objectives with 169 targets, see ICSU (2015) for details.

[13] Generally referred to farm sizes with <10 ha (Graeub et al. 2016).

[14] Crop calorie requirements above domestic production and imports, now and in the future.

et al. 2008; Porter et al. 2014; Wheeler and Braun 2013; Rosenzweig et al. 2014; Cisneros et al. 2014). Climate change might further limit the potential for intensification of production (Pugh et al. 2016), paired with the present degradation of ecosystems, poses a threat to the long-term sustainability and the potential reprint of the Green Revolution's success (Pingali 2012).

Given the clearly intricate outlook for the co-evolution of the human-environment system, the question arises: Does a safe and just space for humanity exist, as delineated by the complex line of SDG targets? Under which conditions does it exist, and how would a viable path look like to reach it? After all, applying human ingenuity to achieve global food security against a background of climate change and increasingly scarce freshwater resources, while staying within the safe operating space of the Earth system (Figure 1.3), is one of the greatest challenges for the 21st century (e.g. Tilman et al. 2002; Foley et al. 2011; Godfray and Garnett 2014; Rockström et al. 2016).

1.1.4. Planetary opportunities in sustainable intensification

The widely promoted term of sustainable intensification of agriculture — how to enhance agricultural productivity while reducing its environmental impacts[15] — is now considered by many a viable resort to address these challenges (The Royal Society 2009; Foresight 2011; Foley et al. 2011; Tilman et al. 2011; Garnett et al. 2013; Godfray and Garnett 2014; Rockström et al. 2016). The academic debate got past the two-dimensional clash of "growth without limits" or "limits to growth". With the societal commitment to a sustainable future the paradigm established that we need to focus on growth within limits, i.e. "abundance within planetary boundaries" (Rockström and Klum 2015). This middle ground forms the nexus in which to move beyond a focus on biophysical limits only and toward solution-oriented research, developing pathways to exploit "planetary opportunities", as advocated by Ruth De Fries et al. (2012).

In fact, there are profound opportunities for action within the food system that can ground cautious optimism. Various farming systems are characterized by significant yield gaps[16] with prevailing low agricultural productivity (<1.5 t/ha). Particularly in Sub-Saharan Africa (SSA) yields are often no greater than in the Roman Empire (Molden 2007) and historical production increase mainly

[15]Sustainability, in the context of agricultural impacts on the environment, is defined hereinafter with respect to the safe operating space (Rockström and Karlberg 2010). A more extensive and profound definition of sustainable agriculture, in the light of agro-ecology, can be found in e.g. Pretty and Hine (2001).

[16]"The difference between farmers' yields and technical potential yields achieved using the latest varieties and under the best of conditions" (FAO et al. 2015).

originated from land expansion (Wani et al. 2009; Alexandratos and Bruinsma 2012). This indicates a substantial scope for yield gains through mitigation of nutrient and water deficiencies, particularly in developing countries — where the food gap is largest (Mueller et al. 2012; *Global Yield Gap Atlas* 2015; Zhang et al. 2016; Ray and Foley 2013).

There are repeated calls for a second Green Revolution (e.g. Conway 1999; Annan 2003; Ki-moon 2008), but now with the recognition of its limitations and the focus on environmentally sound strategies (Faurès et al. 2007; Rockström et al. 2016). Proposals to avoid the acceleration of environmental degradation include the halting of agricultural expansion and the increase in agricultural water productivity (e.g. Rockstrom et al. 2007; Foley et al. 2011; United Nations 2015a). Not only from a water perspective, agro-ecological farming techniques are vital to improve yields and climate resilience among underperforming and smallholder systems and are therefore an important component of sustainable intensification of agriculture (Seufert et al. 2012; Reganold and Wachter 2016; Rockström et al. 2016).

Naturally, opportunities within the food system do not only relate to increasing production, other dimensions including food waste and diet requirements are discussed in Chapter 6. But as its most substantive component, main principles for sustainable intensification of agriculture are evident: (I) improving efficiency in the use of resources, (II) expand or redistribute inputs to underperforming systems, and (III) conserve and enhance natural ecosystems (e.g. FAO 2014c). While such ideas consolidate, there is a research gap how to achieve these goals at global scale. Many promising ideas and local solutions prove successful (e.g. Pretty et al. 2006; Searchinger et al. 2013), but knowledge of how to transform agricultural systems across scales, in respect of various limiting biophysical, institutional, economic, and cultural factors, is largely missing. Despite the prominent position in the 2030 Agenda, the global potential of sustainable intensification of agriculture, and especially the water dimension therein, is widely unknown. To that extent, it remains a multilayered scientific challenge, or in other words, a challenge for human ingenuity, to render opportunities and viable pathways toward the safe and just space for humanity.

1.2. Water as key factor: between scarcity and optimism

Freshwater contributes fundamentally to human well-being and to the resilience of social-ecological systems. While maintaining ecosystem functions, water is inextricably linked to poverty reduction, economic growth, food security — and therefore at the very core of sustainable development (World

Water Assessment Programme 2015b). As emphasized across the 2030 Agenda, water is central to attaining most, and arguably all, of the SDGs (ECOSOC 2016a). It comes down to water, because global freshwater resources are scarce and heterogeneously distributed across populations and therefore inequalities exist in water access (Carr et al. 2015). Apart from food production and industrial use, each person needs 20 - 50 l of clean water each day for drinking and hygiene. Between 1960 and 2005, the percentage of the world population under chronic water stress (<1000 $m^3/cap/yr$) increased from 9% to 35% (Kummu et al. 2010). As the total freshwater demand across sectors is projected to increase by a global 55% by 2050, in some countries even by 100%, to meet SDG targets (World Water Assessment Programme 2015b; SEI 2005) — in the face of climate change and given limited potential for major water diversions across regions — global freshwater resources are put under progressive pressure (Vörösmarty et al. 2005; Gleick and Palaniappan 2010; Cisneros et al. 2014). In the end, due to its complex and transboundary nature, freshwater resources may be regarded as even more valuable than oil — which comes with alternatives, but water might not (Kabat 2013).

In the pursuit of the SDG agenda, water use in agricultural stands out twice. First, over-exploitation of global freshwater resources is the number-one reason to the degradation of ecosystems, particularly wetlands, with far-reaching consequences across the world. Effective means to reset overuse and conserve, protect, and enhance aquatic ecosystems at larger domains are yet to be identified. Second, freshwater is an irreplaceable element of growing food. Worldwide doubling of agricultural productivity appears beyond reach without a profound revolution in agricultural water management. The SDG agenda confidently builds upon opportunities associated with water management in both irrigated and rainfed agriculture that, however, are yet to be devised. This thesis sets out toward touching on both aspects: the challenge to safeguarding water needs to maintain aquatic ecosystems across scales, and the challenge to increasing water productivity through sustainable water management in both irrigated and rainfed farming. More specific directions are detailed hereafter, starting from the domain of water saving potentials of irrigation, over water withdrawal limits and food production that depends on transgressing such, to end with global food production potentials associated with integrated crop water management.

1.2.1. Irrigated farming — ratchet and hatchet

Irrigation expansion was a major component throughout the Green Revolution, especially in Asia. Over the last 50 years irrigated area roughly doubled (FAO 2012; Siebert et al. 2015) and today a quarter of total harvested cropland is under irrigation, producing ∼40% of global cereals (Portmann et al. 2010). Irrigation heavily sustains global agricultural production and contributes to food security worldwide. But it comes at a steep price for natural ecosystems. Irrigation is the single largest user of freshwater, accounting for roughly 70% of total withdrawals, and over 90% in the world's least-developed countries (Gleick et al. 2009; World Water Assessment Programme 2015a). Resources are increasingly depleted for human needs, not only, but most importantly for irrigation (Figure 1.2). In some regions withdrawals exceed 100% of renewable water resources, with devastating consequences (Postel 1999). Groundwater tables fall, wetlands disappear irreversibly, many rivers no longer reach the ocean or inland sinks, and in turn 20% of the global irrigated land area is affected by salinization, waterlogging occurs, water quality deteriorates, and invasive species are introduced and proliferate (FAO 2011; Vörösmarty et al. 2005; Molden 2007). Aquatic ecosystems are thereby rapidly degrading with potentially serious but unquantified costs, imposing the risk of regime shifts away from stable environmental conditions (Vörösmarty et al. 2010; Rockström et al. 2014). Attaining sustainable withdrawals to support safeguarding aquatic ecosystems, in other words respecting the regional boundary for freshwater use, is imperative for sustainable development (United Nations 2015a).

Improving crop water productivity

To these ends, the urgent need for advancing crop water productivity — i.e. to achieve the same yields with less water in both rainfed and irrigated systems — is postulated (e.g. Postel 1999; Molden 2007; IAASTD 2009; World Water Assessment Programme 2015b; ICID 2016). In broad terms, there are two options to increase water productivity, either reduce water losses (i.e. non-beneficial water consumption), or increase the crop or value output per volume of water used.

Water saving potential of irrigation At global scale, irrigation systems operate at surprisingly low efficiency levels — generally only 50% of the diverted water is consumed — as much is lost in the conveyance system or through inefficient application to the plant (Vickers 2001; Molden 2007). Although localized drip irrigation techniques can achieve efficiencies in excess of 95%, only about 3% of irrigated land is operated under such systems worldwide (Postel 1999; FAO 2014b; ICID 2012). While the mere focus on expansion of irrigated land has changed and expansion rates are recently slowing down (Siebert et al. 2015), solutions increasingly focus on modernization of existing infrastructure and management processes, and thus productivity enhancements (Faurès et al. 2007).

Substantial water productivity gains are attributed to upgrades in irrigated agriculture (Molden et al. 2010; Al-Said et al. 2012; 2030 Water Resources Group 2013). But excessive emphasis on water savings paired with misleading definitions of water "losses" and irrigation efficiency have revived an elderly debate on this subject (Seckler 1996; Perry et al. 2009; Gleick et al. 2011; Frederiksen 2011; Christian-Smith et al. 2012; Jia 2012). Two points are important to note therein. First, only part of the water diverted, but not beneficially used up by the plant (i.e not transpired) can be considered a loss. A significant fraction (e.g. percolation, surface runoff) remains in the hydrological system and might be accessible downstream. Only irrigation water that is non-beneficially consumed (e.g. soil evaporation, evaporative conveyance losses, weed transpiration) might form manageable irrigation water losses[17] (see Figure 2.1). This fact is not reflected in the traditional definition of irrigation efficiency (i.e. evapotranspiration by diverted water) and thus merits a revision. Second, pursuits to increase irrigation efficiency do not necessarily translate into reduced water withdrawals, as farmers — in the absence of operative water legislations — generally rather expand irrigation or switch to higher value crops, instead of losing water allocations. Unchanged water diversion paired with more efficient systems results in reduced return flows into the river, which can have adverse effects for downstream users (Ward and Pulido-Velazquez 2008). Besides these valid arguments, and with the notion that irrigation efficiency and water productivity is scale-dependent, any reduction in non-beneficial consumption through irrigation upgrades improves the overall crop water productivity at basin level.

Even though the extent of irrigated areas is relatively well documented (Siebert et al. 2005; Siebert et al. 2015), current knowledge about applied irrigation systems and their performance is confined to rough indicative estimates, generally at country level. Available global irrigation efficiencies are static in time and space and largely neglect dependencies on local biophysical conditions (e.g. Rost et al. 2008b; Sauer et al. 2010). Empirical challenges associated with the separation of beneficial (crop transpiration) and non-beneficial water consumption — often pooled in the term evapotranspiration (see Figure 1.4) — give reason to flawed definitions to irrigation efficiency, and form the origin of limited water saving assumptions associated with efficiency improvements (e.g. Seckler 1996; Frederiksen and Allen 2011; Perry and Hellegers 2012).

Dynamic quantitative water accounting and local net effects of irrigation transitions in account of non-trivial water trade-off dynamics along the river network are difficult to assess with currently available methods, particularly at global scale (Munia et al. 2016). Although global agro-hydrological

[17] Accordingly, hereinafter "irrigation losses" always refer to consumptive losses.

models provide appropriate infrastructure to address such issues, irrigation systems are insufficiently represented therein and generally associated with exogenous efficiency parameters (e.g. Siebert and Döll 2010; Elliott et al. 2014, see Section 2.2). In order to contribute on quantitative grounds to the somewhat gridlocked debate on saving potentials, to refine our understanding of irrigation system performance, and to advance estimates of global water consumption in agriculture, a mechanistic representation of irrigation processes across scales is needed. This involves spatially and temporally explicit simulation of irrigation fluxes, to be partitioned into crop transpiration, soil evaporation, surface runoff, drainage and conveyance processes, in direct coupling with vegetation dynamics, climate, soil, land-use, and management properties — which has yet to be assessed for multiple crop types and at global scale (see Research Question 1).

Crop per drop intensification The second avenue for increasing water productivity, i.e. increasing the yield output per water used, includes agronomic practices such as water harvesting, supplemental irrigation, and soil and water conservation[18]. These measures are detailed below (Section 1.2.2).

Maintaining riverine ecosystems

Safeguarding aquatic ecosystems is a global priority, as outlined above. Riverine and estuarine ecosystems provide life-supporting functions that, in turn, depend on the quantity, timing, and quality of river flows (Falkenmark et al. 2004; Reid et al. 2005). Such water allocations to maintain a fair ecosystem status and thus human livelihoods are referred to as Environmental Flow Requirements (EFRs) (Acreman and Dunbar 2004; Brisbane Declaration 2007).

Global freshwater boundary Rockström et al. (2009c) and Steffen et al. (2015) define the planetary boundary for human freshwater use (PB-Water) as the maximum global amount of freshwater that can be appropriated by humans (i.e. blue water[19] consumption, abstracted from rivers, reservoirs, lakes and aquifers). Transgressing this threshold would impose a high probability of water-induced regime shifts with detrimental effects on human societies. Despite the significance of this initial quantification, it is not beyond critical conceptual caveats. Provisionally set at 4000 km^3/yr,

[18] Other factors not related to water management, such as advances in breeding and soil fertility management are beyond the scope of this thesis (see e.g. Foley et al. 2011, for an overview).

[19] "Blue water resources are defined as the generated runoff stored in aquifers, [rivers], lakes, wetlands and reservoirs. Green water resources are defined as the infiltrated rainfall in the unsaturated soil layer forming soil moisture that is on its way to evaporate back to the atmosphere." (Falkenmark et al. 2009).

PB-Water builds upon a top-down approach that juxtaposes global renewable freshwater resources and water volumes needed to avoid water stress, arbitrary treated as a global average. A key component missing, is the spatially explicit account of EFRs as a function of local water availability to safeguard the aquatic habitat. Rockström et al. (2009c) subtract a general 60% of total accessible freshwater volume in account of water stress prevention, neglecting spatiotemporal pattern. In order to enhance PB-Water's credibility, to allow for a refined evaluation of our current vicinity to its limits, and to develop pathways to stay within the safe operating space for freshwater, PB-Water merits conceptional revision and reassessment of its quantitative foundation. In pursuing such, we seek a more context-specific, bottom-up approach in which local ecosystem needs set boundaries for human water use, including the account of spatial patterns in EFRs (see Research Question 2).

Local freshwater boundary Due to the fact that PB-Water defines a highly aggregated concept — even though not yet transgressed at global level — it oversees local impairments and already severe flow alterations (Smakhtin et al. 2004; Pastor et al. 2014). Accordingly, Steffen et al. (2015) also define a local boundary for freshwater withdrawal that is compatible with local EFRs of rivers.

Since EFRs are clearly transgressed along many river stretches today (Postel 1999; Poff and Zimmerman 2010; Richter et al. 2012), approaches to safeguard riverine ecosystems have been determined in case study regions, based on various methods (Poff et al. 2010). A number of legislations and policy recommendations have been established accordingly (Brisbane Declaration 2007; Le Quesne et al. 2010; European Comission 2015), but methodological, institutional, and financial challenges in the quantification of EFRs across scales hinder its broader (and transboundary) implementation. It remains a challenge that EFRs become socially relevant against other water users such as agriculture and industry (Smakhtin 2008; Poff and Matthews 2013). The central issue to inform actionable policy making at larger domains is to establish a uniform method to allocate the fraction of pristine flow that should remain untouched to sustain a "fair" environmental state across all river basins, despite multilayered dependencies on other environmental features (Pastor et al. 2014; Poff and Matthews 2013).

Moreover, to quantitatively underpin the insufficiently specified SDG targets 2.4 "sustainable food production system" and 6.4 "sustainable freshwater withdrawals", we need to establish large-scale robust assessments of current flow alterations and EFR transgressions, and eventually assess the degree to which today's irrigated food production depend on these volumes. However, dynamic process-based model simulations addressing these questions globally, including environmental and

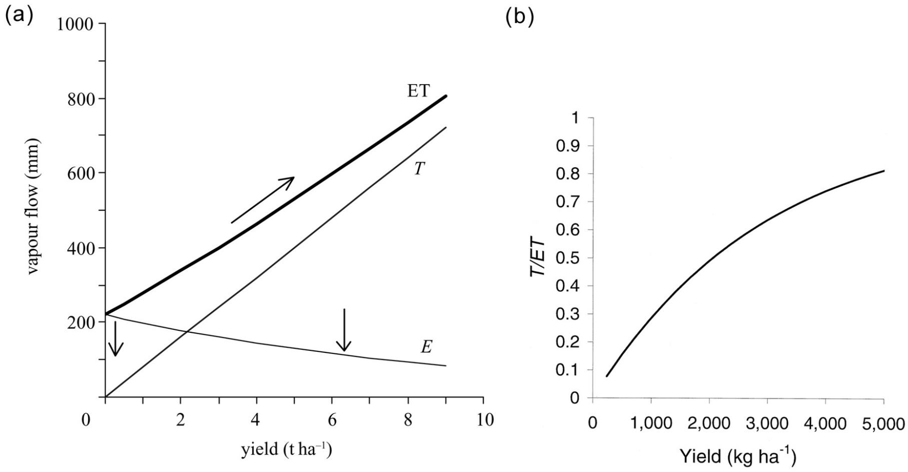

Figure 1.4.: Water saving potentials of low-yielding green water systems. Chart **(a)** illustrates the general relationship between crop yield and the different water flow components: non-beneficial evaporation (E), beneficial crop transpiration (T), and the combined evapotranspiration (ET) (source: Rockström (2003)). Chart **(b)** shows the resulting ratio of T and ET as a function of grain yield (source: Rockström and Falkenmark (2000)).

agronomic feedback effects and trade-offs along the river network are not available until today (see Research Question 3).

1.2.2. Rainfed agriculture — the crux of a new Green Revolution

The contributions of irrigation to global food security have been tremendous and will even increase in the future (World Water Assessment Programme 2015b; Faurès et al. 2007), but its overall scope appears far from sufficient for the SDG agenda (Rockstrom et al. 2007). Substantial and new freshwater allocations are required to bring current food production on a par with future demands: 5200 km^3/yr of additional blue and green water might be needed by 2050 under current water productivity levels (SEI 2005; Rockstrom et al. 2007). However, such volumes have to originate to 85% from green water on current rainfed land, i.e. through maximizing water productivity, as arable land is scarce and irrigation expansion limited (SEI 2005). The majority of food production at global level — currently about 60% — remains rainfed for the foreseeable future (Siebert and Döll 2010; FAO 2011).

The first Green Revolution focussed on areas with sufficient precipitation or irrigation, where returns were high (Pingali 2012). Tackling today's yield gaps requires more marginal regions to come into focus, with the defining characteristics of water constraints in semi-arid, and mostly rainfed regions. In these drought-prone and low-yielding systems, the lack of water is of principal concern, because it subsists a co-limitation of nutrients and water. Replenishing soil fertility will often not have much effect, until sufficient soil moisture becomes available to the plant (Oweis and Hachum 2006). Yet, an important aspect is that it is often not about the total amount of precipitation per year that imposes greatest problems, but unreliable and erratic rainfall (i.e. dry spells and periodic water scarcity) (Wani et al. 2009). In addition, poor farm water management characterized by excessive on-farm water losses in semiarid tropical systems provokes root zone drought and resulting low yields (1-2 t/ha) (Oweis and Hachum 2006; Rockstrom et al. 2007). On average, a large fraction of available precipitation (and irrigation) water runs off unused, evaporates non-beneficially from bare soils, or percolates below the plant root zone (see Figure 5.1). Such losses on non-beneficial green water flows lead to a nonlinear relationship between yield growth and water consumption (fraction of non-beneficial consumption is larger at the lower end of yields, Figure 1.4), which indicates a particularly great opportunity to improve water productivity at the low-yield range in savanna agro-ecosystems, and to lift current staple yields (such as maize, millet, and sorghum) from 1–2 t/ha to 3–4 t/ha (Rockström et al. 2003). A doubling of yields is achievable with current know-how through relatively small manipulations of rainwater partitioning in drought prone areas, such as sub-Saharan Africa (Rockström and Falkenmark 2000; Molden 2007). Here lies the worldwide largest untapped potential to safe water in food production, in the same regions where population growth and thus food demand growth is fastest (Falkenmark et al. 2009). These facts render remarkable hydro-climatic opportunities for on-field water management interventions in rainfed farming to improve yield levels, smallholder climate resilience, and — most importantly — livelihoods of the poor (Biazin et al. 2012).

Climate change with altered rainfall patterns might impose additional stress on agricultural systems, particularly for smallholders in semi-arid regions (Falkenmark et al. 2009; Porter et al. 2014). Field studies, however, demonstrate a wide spectrum of long-known agro-ecological practices to increase plant water availability and thereby climate resilience through e.g. maximizing soil infiltration, collecting surface runoff for supplemental irrigation, and alleviating soil evaporation (e.g. Fox and Rockström 2003; Welderufael et al. 2008; Araya and Stroosnijder 2010). Such readily available measures are being implemented sporadically around the world, leaving untapped huge potential to scale up (Barron et al. 2015; Mati et al. 2007; Searchinger et al. 2013). But given the heterogeneity of farming systems and downstream water trade-offs, it is difficult to understand its cumulative effect and overall potential at the landscape or even global scale (Ngigi 2003; Kahinda et al. 2007). It lacks agro-hydrological modeling approaches to assess and advocate its global scope, as these measures are — even though central to sustainable intensification of agriculture — currently insufficiently represented among international development strategies (Rockström and Falkenmark 2015).

Finally, to exploit planetary opportunities in farm water management in the vein of a new Green Revolution, management interventions must focus on integrating measures in both green and blue water systems. Both components are crucial, but the attainable extent of synergy at global level is insufficiently quantified (e.g. Molden 2007; IAASTD 2009; Rost et al. 2009; Brauman et al. 2013). A systematic global assessment of integrated crop water management in rainfed and irrigated agriculture under current climate, but also incorporating state-of-the-art climate change scenarios, is still lacking (see Research Question 4).

1.3. Methodological rationale

In pursuing such an intricate line of research, and at global scale, it is essential to work with a simplification of the reality, while representing most important Earth system processes at a workable degree of detail. In other words, the "macroscope" is in demand (Schellnhuber 1999). Recent advances in global modeling capacity play a critical role in understanding Earth system processes and their feedbacks. Such models can render the portfolio of possible planetary futures, and might thus influence decisions to shape it (e.g. IPCC 2013).

While statistical models make use of the power of empirical relationships observed and extrapolate these to new grounds (e.g. Lobell et al. 2008; Schlenker and Lobell 2010), they are by design constrained to straightforward causal dependencies. To address more complex questions that refer to the interdependency of biophysical and management factors and especially their feedbacks at larger scales — for example: How do irrigation water trade-offs propagate along the river network and affect food production at basin level? — mechanistic, spatially distributed models are the only available tool today. Process-based Dynamic Global Vegetation Models (DGVMs), such as the LPJmL model I use herein, are suited tools to play out delicate interactions between Earth system processes, while solving the fully coupled terrestrial carbon, energy, and water balance, including vegetation dynamics and management interventions.

Being under continuous development since around the year 2000, its core LPJ derives from the BIOME family of biogeographical equilibrium models (Prentice et al. 1992; Haxeltine and Prentice

1996) and was originally developed to simulate the composition and dynamic distribution transitions of terrestrial vegetation under climate and human land use alterations (Sitch et al. 2003). Under the extended name LPJmL, it was subsequently expanded to also cover a hydrological module and river routing processes (Gerten et al. 2004; Rost et al. 2008a) and a representation of agriculture, i.e. cropland and pastures (Bondeau et al. 2007). These developments added to the unique strength of the model to simulate water and carbon fluxes in direct coupling with the establishment, growth, productivity, and competition of major natural (9 generic plant types) and agricultural (12 generic crop types, rainfed or irrigated) processes. Contrary to statistical models, LPJmL simulates underlying key ecosystem processes such as photosynthesis, respiration, carbon allocation, water partitioning, soil water balance, in a detailed, explicit, and mechanistic manner, with high resolution in time (daily) and space (>67,000 grid cells covering global terrestrial land surface) and comparatively low computation requirements. This allows to assess for instance climate change impacts with altered patterns in precipitation, temperature, and CO_2 concentration on plant growth with dynamic feedbacks of soil water content, stomatal conductance, and grain production.

Ongoing model enhancements (see Section 2.3.2) continuously expanded the level of detail, which improved performance skills and credibility, and progressively opened the scope of this agro-biosphere model toward more complex inter-disciplinary research questions. Today, LPJmL is one of the most advanced and most comprehensive DGVMs worldwide, offering a unique and internally consistent modeling framework to help understand the interference of humans with the food production system. LPJmL's sophisticated water balance allows to assess water trade-offs within river basins, but with respect to my research questions (see below), irrigation was by now insufficiently represented and schemes to simulate rainwater management and environmental flow requirements were lacking. Toward these ends, I enhanced the current model version to adequately support my research agenda, detailed in Section 1.4.

To illustrate LPJmL's water balance and the improved irrigation processes, Figure 2.2 outlines my newly devised irrigation water routine, and an extended account of the model's general water balance and river routing is condensed in Figure A.5. Studies describing relevant previous model development are listed in each chapter. For development, calibration, and validation of the work in this thesis, I used observational data from different sources such as AQUASTAT (FAO 2014b) for irrigation system distribution, FAOSTAT (FAO 2012) for crop yield statistics, and the Global Runoff Data Centre (GRDC 2016) for discharge observations. Evaluations of modeling performance are provided in each chapter (e.g. Figure 4.4) and more generally reviewed in Section 6.2. Beyond this thesis, also other data sources including carbon flux measurements and remote sensing imagery

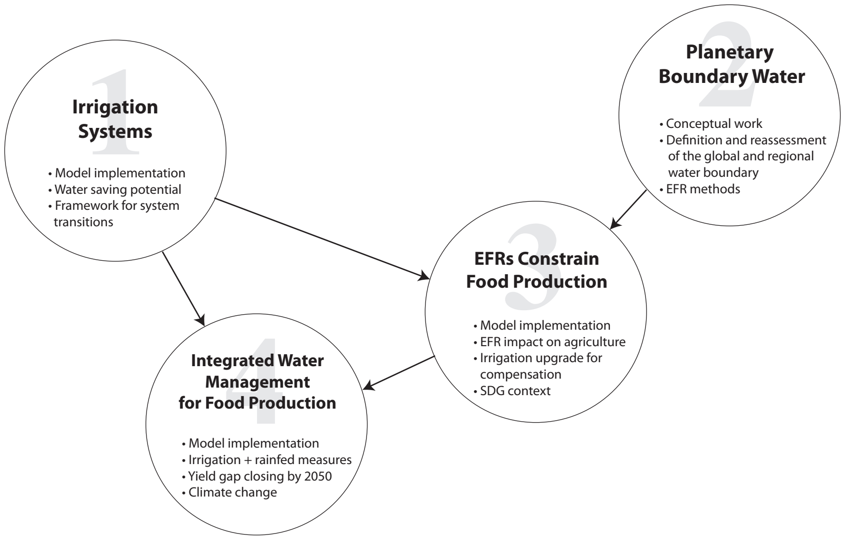

Figure 1.5.: Outline and linkings of research studies.

(e.g. Jägermeyr et al. 2014) have been used for LPJmL evaluation. Alternative methodological approaches are discussed within each of the following studies.

1.4. Research outline

The dual pressure on farm water management in attaining the SDGs — i.e. supporting a doubling of agricultural productivity while maintaining sustainable freshwater withdrawal — outlines the broader background of this thesis. My main objective is to comprehensively quantify planetary opportunities in farm water management aimed to secure future food production — a global social foundation — within the safe operating space for freshwater use. The focus is on the following research questions (Figure 1.5 provides an overview), which are motivated above and build a progression from the role of irrigation in global food production, focussing on associated water saving potentials (Chapter 2), to resulting alterations of the hydrological cycle, with an reassessment of PB-Water (Chapter 3), to the spatially explicit quantification of food production's dependency on such water-overuses (Chapter 4), and finally to the systematic assessment of yield-increasing opportunities in integrated farm water management (Chapter 5):

Study 1 What is the water saving potential of efficiency transitions in global irrigation, without compromising food production?

In this study, I investigate how spatial patterns in irrigation efficiency are distributed at global level, and which (biophysical) drivers can explain them. Therefore, I implement a new framework into LPJmL that mechanistically represents major global irrigation systems and that also provides a scheme to study irrigation transitions. Based on this enhanced model and irrigation improvement scenarios, I contextualize and quantify how much irrigation water could be saved through irrigation upgrades across crop types and river basins. Finally, I show to which degree transitions in irrigation efficiency could improve global crop water productivity and which regions demonstrate particular potential. This new model builds the methodological foundation for my following studies (Chapter 2).

Study 2 Where would the planetary boundary for human freshwater use be positioned, if it was based on a spatially explicit assessment of environmental flow requirements?

This study reviews the conceptional basis of PB-Water and reassesses its quantitative positioning in account of geographical patterns of EFRs. Five different hydrologic methods are used to calculate EFRs at the grid-cell level. On these grounds, this study evaluates how close current human water use is to the new estimate of PB-Water (Chapter 3).

Study 3 If human water use was to be constrained by the EFRs, by how much and where would food production decrease?

In this study, I operationalize the model-based quantification of EFRs across river basins through implementing a scheme into LPJmL that dynamically represents safeguarding environmental flows worldwide. Advancing the provisional post-process assessment in Study 2, this study identifies where and by how much EFRs are transgressed today, and then, quantifies the water volume that is withdrawn unsustainably from global river systems for irrigated food production and other human water uses. The central question is to what degree current food production would be affected if global policies came into practice to safeguard EFRs. To complement this analysis, I evaluate if efficiency transitions in irrigation could reset water over-exploitation (following approaches developed in Study 1) (Chapter 4).

Study 4 To which extent could integrated crop water management in rainfed and irrigated farming close the future global food gap?

This study widens the scope even further by assessing food production potentials of combined interventions in irrigated and rainfed systems, across different scales, and without using additional land or water resources. First, I investigate by how much food production could be intensified through transitions to more efficient irrigation systems, using the model infrastructure in Study 1 and 3. Second, I assess the global potential to intensify food production through agro-ecological techniques, such as rainwater harvesting and mulching. This requires to enhance the model and represent these techniques in a process-based manner. In combination, I finally assess the comprehensive potential to defeat current water deficiency through both irrigated and rainfed interventions in synergy. This chapter provides quantitative estimates of planetary opportunities in sustainable intensification of food production today, but also in the face of climate change and population growth by 2050 (Chapter 5).

Overall, this research agenda is designed to elaborate a comprehensive assessment and understanding of the role of improved agricultural water management in securing future food production while respecting environmental boundaries. All four studies contribute consecutively and from different angles to this research agenda.

Chapter 2, 3, and 5 are published, Chapter 4 is currently in revision, all in peer-reviewed, ISI-listed journals. Answers to the research questions are provided with the synthesis in Chapter 6. Therein, the key findings are discussed with respect to methodological uncertainties and caveats, and then placed in a wider context. A final section with general conclusions completes this thesis.

Chapter 2.

Water savings potentials of irrigation systems: global simulation of processes and linkages

An edited version of this chapter, supplemented by appendix A, has been published in the journal *Hydrology and Earth System Science*:

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2.1. Abstract

Global agricultural production is heavily sustained by irrigation, but irrigation system efficiencies are often surprisingly low. However, our knowledge of irrigation efficiencies is mostly confined to rough indicative estimates for countries or regions that do not account for spatio-temporal heterogeneity due to climate and other biophysical dependencies. To allow for refined estimates of global agricultural water use, and of water saving and water productivity potentials constrained by biophysical processes and also non-trivial downstream effects, we incorporated a process-based representation of the three major irrigation systems (surface, sprinkler, and drip) into a bio- and agrosphere model, LPJmL. Based on this enhanced model we provide a gridded worldmap of irrigation efficiencies that are calculated in direct linkage to differences in system types, crop types, climatic and hydrologic conditions, and overall crop management. We find pronounced regional patterns in beneficial irrigation efficiency (a refined irrigation efficiency indicator accounting for crop-productive water consumption only), due to differences in these features, with lowest values (<30%) in South Asia and Sub-Saharan Africa and highest values (>60%) in Europe and North America. We arrive at an estimate of global irrigation water withdrawal of 2469 km^3 (2004–2009 average); irrigation water consumption is calculated to be 1257 km^3, of which 608 km^3 are non-beneficially consumed, i.e. lost through evaporation, interception, and conveyance. Replacing surface systems by sprinkler or drip systems could, on average across the world's river basins, reduce the non-beneficial consumption at river basin level by 54% and 76%, respectively, while maintaining the current level of crop yields. Accordingly, crop water productivity would increase by 9% and 15%, respectively, and by much more in specific regions such as in the Indus basin. This study significantly advances the global quantification of irrigation systems while providing a framework for assessing potential future transitions in these systems. Here presented opportunities associated with irrigation improvements are significant and suggest that they should be considered an important means on the way to sustainable food security.

2.2. Introduction

A major humanitarian challenge for the 21st century is to feed a growing world population in face of climate change and sustainability boundaries (e.g. Foley et al. 2011). In addition to requiring institutional changes, global crop production is likely to have to double to meet the demand by 2050 (Tilman et al. 2011; Alexandratos and Bruinsma 2012; Valin et al. 2014). At present, irrigation is a key component of agriculture; global cereal production would decrease by 20% without irrigation (Siebert and Döll 2010), and climate change and population growth will further enhance its role in future (Neumann et al. 2011; Plusquellec 2002). In the past 50 years irrigated area roughly doubled (FAO 2012; Siebert et al. 2015) and today about 24% of the total harvested cropland is irrigated, producing >40% of the global cereal yield (Portmann et al. 2010). Irrigation is the single largest global freshwater user, accounting for ∼70% of water withdrawals and 80%–90% of water consumption (Gleick et al. 2009).

However, as the planetary boundaries for freshwater use and land-system change are being approached rapidly or are already exceeded, there is little potential for increasing irrigation or expanding cropland (Steffen et al. 2015; Gerten et al. 2013). Thus, production gaps must be closed by sustainable production increases and higher cropping intensities on currently harvested land by either increasing rainfed yields or optimizing the water productivity of irrigated cropping systems and ecologically sensitive transforming rainfed systems into irrigated systems (Alexandratos and Bruinsma 2012).

Indeed, current irrigation efficiencies are often below 50%, as much of the diverted water is lost in the conveyance system or through inefficient application to the plants. The magnitude of these losses is determined primarily by the irrigation system (e.g. sprinkler, surface, drip) but also by meteorological and other environmental conditions. At first glance, the often low efficiency suggests a high potential for water savings. However, only water that leaves the system without a benefit for crop growth, such as evaporation from bare soil and other non-beneficial components (e.g. weed transpiration, Figure 2.1), should be considered a manageable loss (e.g., Keller and Keller 1995). As the different water fluxes are difficult to separate empirically, non-beneficial consumption remains a poorly measured and studied element of the irrigation water balance (Gleick et al. 2011) and associated specific saving potentials are largely neglected in discussions on irrigation improvements (e.g. Perry et al. 2009; Frederiksen and Allen 2011; Simons et al. 2015). Also, while reducing non-beneficially consumed water clearly enables local yield increases using the same amount of water (Luquet et al. 2005; Molden et al. 2010; Al-Said et al. 2012), it inevitably reduces return flows as well. This can have mid-term negative effects on crop production through faster soil water depletion or less available water for downstream users (Ward and Pulido-Velazquez 2008). The net effect at the basin level, accounting for downstream effects, is difficult to track with current methods (Nelson et al. 2010; Jia 2012; Perry and Hellegers 2012; Simons et al. 2015).

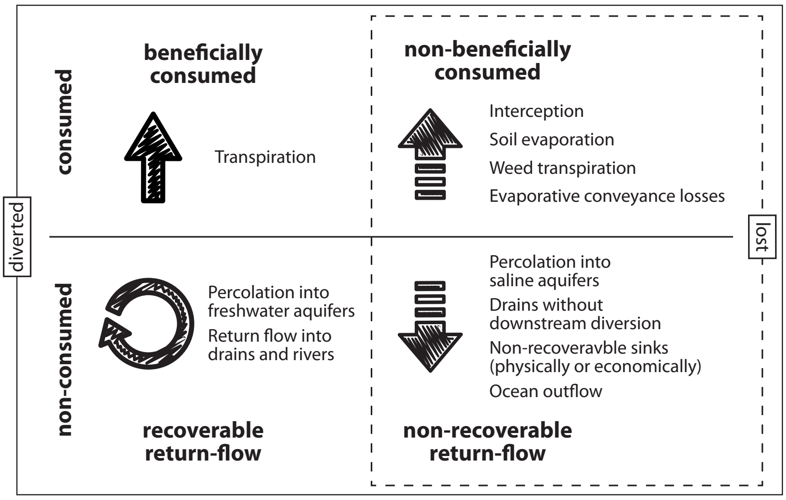

Figure 2.1.: Pathways of irrigation water fluxes. All diverted water is either consumed (beneficially or non-beneficially), or re-enters rivers, reservoirs and aquifers, which makes it recoverable through return flow. Non-beneficial consumption and non-recoverable return flow can be considered losses (at the basin scale).

These non-trivial dynamics currently revive an earlier debate on the water saving potential of irrigation improvements (Seckler 1996; Cooley et al. 2008; Ward and Pulido-Velazquez 2008; Perry et al. 2009; Pfeiffer and Lin 2009; Christian-Smith et al. 2012; Brauman et al. 2013; Pfeiffer and Lin 2014; Simons et al. 2015). Previous studies of water saving potentials may have been too pessimistic, as they implicitly assume that total irrigation water consumption is beneficial (Burt et al. 1997; Perry et al. 2009; Simons et al. 2015). Furthermore, estimates of irrigation efficiencies are mostly based on rough assumptions for regions or countries, without dynamic quantitative water accounting. Advanced estimates of global agricultural water consumption, and of water saving and water productivity potentials at basin level require a spatially and temporally explicit and process-based simulation of the irrigation water balance. That is, the performance of irrigation systems shall be represented mechanistically, in direct coupling with vegetation dynamics, climate, soil, and land-use properties.

In global agro-hydrological models irrigation systems are insufficiently represented in this regard. For instance, many models only consider net irrigation requirements without accounting for water losses during conveyance or application (Haddeland et al. 2006; Siebert and Döll 2010; Stacke and Hagemann 2012; Elliott et al. 2015). Others employ globally constant indicative efficiency values from e.g. Brouwer et al. (1989), as a static input (e.g. Wriedt et al. 2009; Wada et al. 2013). These estimates were regionalized for the dominant irrigation system in each country by Rohwer et al. (2007) and since have been often referenced (e.g., Rost et al. 2009; Wriedt et al. 2009; Wada et al. 2011; Schmitz et al. 2013; Chaturvedi et al. 2015; Elliott et al. 2014), yet still until today they remain rough indicative estimates. Assessments of future irrigation water requirements under climate change also have been carried out using static and country-based efficiencies, without accounting for local biophysical conditions (Fischer et al. 2007; Konzmann et al. 2013; Elliott et al. 2014). Sauer et al. (2010) endogenously determined the irrigation system based on biophysical and socioeconomic factors, but water fluxes are not simulated. To our knowledge, besides LPJmL, PCR-GLOBWB (Wada et al. 2014) is the only global model that intrinsically partitions applied irrigation water into daily evapotranspiration and percolation losses per unit crop area based on surface and soil water balance, yet only for two crop classes without partitioning beneficial and non-beneficial water consumption. LPJmL as described herein now solves the complex irrigation water balance with considerable spatial and temporal detail (see Section 2.3.2).

With the aim of studying global irrigation systems based on an integrated process-based approach, we implement a representation of the three major irrigation systems (surface, sprinkler, and drip) for various crop functional types (CFT) into the global bio-agrosphere model LPJmL. The new irrigation module exceeds previous global modeling studies and replaces an existing scheme that is based on static efficiencies (Rost et al. 2008b). It explicitly takes into account the daily surface and soil water balance (potentially limiting water withdrawal) and partitions irrigation water fluxes into transpiration (T), soil evaporation (E), interception loss (I), surface and subsurface runoff (R) and deep percolation (Dr), depending on daily weather conditions and solving the water and energy balance. Furthermore, we develop a new global dataset on the distribution of irrigation systems for each CFT at the 0.5° grid-level by combining AQUASTAT data on irrigation system distribution, cropland extent, and irrigation suitability.

Based on this data and modeling framework, we first present a spatially explicit, process-based global distribution of irrigation efficiency estimates based on a new, more precisely defined indicator: beneficial irrigation efficiency (E_b). Second, we provide new estimates for irrigation water components on the basis of significantly more spatial, temporal and process details compared to previous studies. Third, we investigate at basin level how much non-beneficially consumed water could be saved, and by how much crop water productivity could be increased, if irrigation system efficiencies were improved.

2.3. Methodology

2.3.1. Definition of irrigation efficiency

Irrigation efficiencies (E_i) are difficult to compare between studies, because there are various approaches to their definition and field measurements are difficult to assess (Burt et al. 1997; Perry et al. 2009). The generic definition is as follows (e.g. Bos and Nugteren 1990; Seckler et al. 2003; Jensen 2007):

$$E_i = \frac{W_c}{W_d}, \tag{2.1}$$

where W_c is water consumption (evaporation from soil and water surfaces, transpiration, and interception) and W_d is water withdrawal, i.e. the amount of water diverted from rivers, reservoirs, lakes, or groundwater. The remainder, the non-consumed water, is the return flow (W_r), i.e. surface and lateral runoff and drainage or deep percolation. It thus equals the difference between diverted and depleted water (Lankford 2006).

Water consumption includes both beneficial and non-beneficial components. Plant transpiration belongs to the first category, as it occurs simultaneously with CO_2 uptake through the stomata and thus contributes to biomass build-up. The non-beneficial components, which are often of sizeable magnitude, include evaporation from soil and water surfaces, interception losses from vegetation canopies and puddles, and weed transpiration. Such non-beneficially consumed water is lost from the system and forms a real saving potential that is not reflected in E_i (Figure 2.1). This has already been proposed by Burt et al. (1997), but due to technical challenges to its measurement, evaporation could not be separated from beneficial consumption and thus E_i was established as the common efficiency indicator. Here, we refine that definition and emphasize the use of a more precisely defined indicator, *beneficial irrigation efficiency* (E_b), given by the ratio of transpiration (T) and withdrawals:

$$E_b = \frac{T}{W_d} = E_c \times E_f. \tag{2.2}$$

E_b is further the product of conveyance efficiency (E_c) and field application efficiency (E_f). E_c relates to water transport losses from the source to the field:

$$E_c = \frac{W_f}{W_d}, \tag{2.3}$$

where W_f is the amount of water that reaches the field. E_f relates to the water application on-field:

$$E_f = \frac{T}{W_f}. \tag{2.4}$$

Irrigation efficiency thus defined is scale-dependent, both in time and space. E_b is a valid indicator for assessing irrigation system performance at the field (and grid cell) scale, but it does not allow assessing water saving potentials at the basin level, since it does not take into account that return flows remain partly available for downstream reuse. In this respect, the term *effective efficiency* was introduced, defined as beneficial consumption (W_{bc}) per unit of water consumed (W_c), which includes that return flows are assumed accessible (e.g. Keller and Keller 1995; Seckler et al. 2003; Jensen 2007). For our analysis of water savings we focus on the reduction of non-beneficial consumption (W_{nbc}), and therefore we employ the inverse of effective efficiency, the *ratio of non-beneficial consumption* and total consumption:

$$RNC = \frac{W_{nbc}}{W_c}. \tag{2.5}$$

Throughout this study irrigation efficiencies are calculated from sums of daily water fluxes over the growing season on the irrigated fraction of each 0.5° x 0.5° grid cell in *mm*. As we use these annual values, water remaining in the soil storage is negligible for calculating irrigation efficiencies.

Moreover, we define crop water productivity as:

$$CWP = \frac{Y_{irr}}{W_{tc}}, \tag{2.6}$$

where Y_{irr} is yield production in *kcal* from irrigated crops and W_{tc} is total (blue and green) crop water consumption in *liters*. The model is able to trace the daily flows of both green water (directly originating from precipitation and infiltrating into the soil) and blue water (diverted from sources like rivers, lakes, reservoirs, and groundwater). Hereinafter, irrigation water fluxes always refer to the unfrozen blue water fraction unless specified otherwise (see Rost et al. (2008b) for details).

2.3.2. Suitability of the dynamic process model LPJmL to simulate irrigation systems

The model LPJmL globally represents biogeochemical land surface processes of vegetation and soils (Bondeau et al. 2007; Rost et al. 2008b; Fader et al. 2010), simulating daily water and carbon fluxes in direct coupling with the establishment, growth, and productivity of major natural and agricultural plant types.

The spatio-temporal distribution of natural vegetation, represented through 9 plant functional types (PFTs), is dynamically simulated based on climatic and carbon dioxide forcing (Sitch et al. 2003). Agricultural land is represented by 12 specified CFTs, a class "others" including a suite of crops collectively parameterized as annual crops, and pastures (Bondeau et al. 2007), all either irrigated or rainfed. The spatial distribution of CFTs and their irrigated fraction is prescribed (see Section 2.3.5).

Photosynthesis modeling in LPJmL follows a modified Farquhar et al. (1980) approach and daily crop carbon assimilation is allocated to harvestable storage organs (e.g. cereal grain) and three other pools (roots, leafs, stems). Sowing dates are dynamically calculated based on climatic and crop conditions (Waha et al. 2012). Crops are harvested when they reach maturity, defined either through a CFT-specific maximum value of daily accumulated phenological heat units or expiration of the growing season. Storage organs are subsequently removed from the field. Root growth and distribution within soil layers is CFT-specific, while the soil profile is discretized into 5 hydrologically active layers and bedrock (Schaphoff et al. 2013).

Plant growth is currently not directly nutrient-limited in LPJmL, yet constrained by temperature, radiation, water and atmospheric CO_2 concentration. We calibrate crop yields with national FAO statistics based on three model parameters (as in Fader et al. 2010) to account for CFT-specific management intensities.

LPJmL partitions precipitation ($prec$) and applied irrigation water into interception, transpiration, soil evaporation, soil moisture, and runoff. Infiltration rate of the surface soil layer is a function of the saturation level (Equation A.1). Surplus water that cannot infiltrate (iteratively in 4 mm slugs) generates surface runoff. Subsurface soil water above saturation runs off in lateral direction, while remaining soil water above field capacity (W_{fc}) percolates to the layer beneath, depending on its soil water content and hydraulic conductivity. Globally, 13 soil types are differentiated, according to their water holding capacity (WHC), hydraulic conductivity and soil texture (Schaphoff et al. 2013). Surface and lateral runoff and seepage groundwater runoff, which is the percolation from the bottom soil layer, are added to cell runoff and are subsequently available for downstream reuse, routed along the river network. While in reality not all return flow is recoverable (due to degradation or inaccessibility; Figure 2.1), LPJmL only considers the eventual outflow to oceans as non-recoverable.

Beneficial water consumption, i.e. transpiration, is calculated as the minimum of atmospheric demand (D), equal to potential evapotranspiration (PET) in the absence of water constraints, and actual root-available soil water constrained by plant hydraulic traits (supply, S). PET is computed after Priestley-Taylor but modified by above-plant boundary layer dynamics (Gerten et al. 2007). If D exceeds S, crops begin to experience water stress (Equation A.1 and A.2). Evaporation is a function of PET, soil water content in the upper 30 cm, vegetated soil cover and radiation energy (Equation A.3). Interception loss (I) is a function of leaf area index (LAI), the daily fractional vegetation coverage, leaf wetness, and PET (Equation 2.10 and 2.11).

Moreover, we account for household, industry and livestock water use (HIL, assumed to be consumed prior to any irrigation; see Section 2.3.5) and include a representation of dams and reservoirs to improve the simulation of available surface water (Biemans et al. 2011).

Thus, water fluxes are simulated in considerable detail, in direct coupling with vegetation dynamics, and responsive to climatic conditions. LPJmL is therefore well suited for studying water fluxes associated with differentiated irrigation systems in an internally consistent and process-based manner.

2.3.3. Implementation of the new irrigation scheme in LPJmL

We implement the three major irrigation systems - surface, sprinkler, and drip - according to their generic characteristics in direct coupling to the model's soil water balance, which overcomes the earlier scheme of fixed efficiencies as in Rost et al. (2008b). Irrigation systems differ in the way they distribute water across the field. Surface systems (basin and furrow combined) flood the field, sprinkler uses pressurized sprinkler nozzles and micro/drip is the most cost-intensive system using localized water application directly to the plants' root zone. Indicative efficiency values (E_i) associated with the three system are roughly 30-60%, 50-70% and 70-90%, respectively (Brouwer et al. 1989; Halsema and Vincent 2012).

In our model, irrigation water is supplied based on daily soil water deficit. Daily net irrigation requirement (NIR, mm) is requested for withdrawal, if S falls below D. We define NIR as the amount of water required in the upper 50 cm soil to avoid crop water limitation. It is calculated to meet field capacity:

$$NIR = max(0, (W_{fc} - w_a)), \tag{2.7}$$

where w_a is the actual available soil water in mm. Due to the above-described system inefficiencies, additional water needs to be requested to meet crop water demand. Therefore, we account for conveyance efficiency and calculate application requirements (AR) for each system, which add up to gross irrigation requirements (GIR, mm), the water amount requested for abstraction (Figure 2.2):

$$GIR = \frac{NIR + AR - Store}{E_c}, \tag{2.8}$$

where $Store$ is a storage buffer (see below).

For pressurized water transportation (sprinkler and drip), E_c is set to 0.95, as we assume inevitable losses from leakage of 5% (Brouwer et al. 1989). We associate surface irrigation with open canal transportation and we further link E_c to the hydraulic conductivity (Ks) of the soil type. E_c estimates from Brouwer et al. (1989) are adopted, see Table 2.1. We assume half of conveyance losses are due to evaporation from water surfaces and the remainder is drainage and added to return flow.

AR is the additional amount of water necessary to distribute irrigation uniformly across the field, indicative of the farmer's estimate of application losses (that are simulated by the model). We calculate AR as a system-specific scalar of the free water capacity:

$$AR = max(0, (W_{sat} - W_{fc}) \times du - w_{fw}), \tag{2.9}$$

where W_{sat} is soil water content at saturation point, in mm; du is the water distribution uniformity scalar, depending on the irrigation system (Table 2.1) and w_{fw} is the available free water (actual soil water content between saturation and field capacity).

Surface irrigation systems use large amounts of water to flood the field in order to uniformly distribute water, which results in considerable surface runoff and seepage (see our analysis below, and Rogers et al. 1997). This is represented through $du = 1.15$, leading to temporary over-saturation of the field. For sprinkler systems, du must not be smaller than 0.55 to securely deliver NIR into the upper 50 cm of the soil (Figure A.1). Drip systems apply water localized to the plant and therefore distribution requirements are much lower, with $du = 0.05$ average yield levels are slightly below the potential (modest form of deficit irrigation), yet allocating salt leaching requirements (Figure A.1).

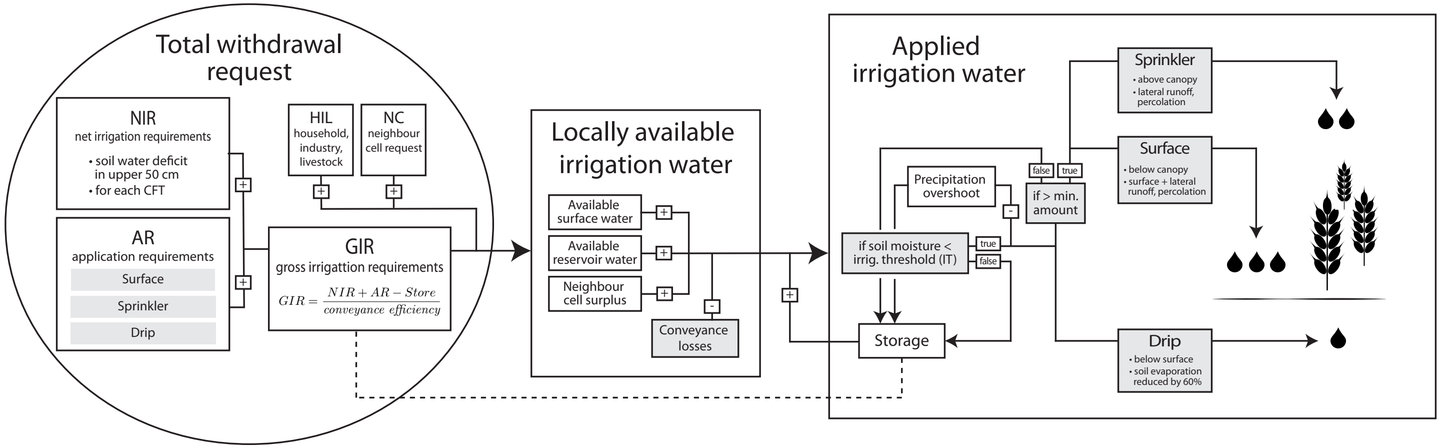

Figure 2.2.: Irrigation water flows in LPJmL. This is a simplified illustration from plant-specific net irrigation requirement to actual field application, variables represented in grey-shaded boxes depend on system-specific parameters that are presented in Table 2.1 below.

Table 2.1.: Parameterization of irrigation systems in LPJmL. Sensitivity analyses for parameter estimates are available in the appendix (Figure A.1 and A.3).

Irrigation system	Distribution uniformity scalar	Conveyance efficiency[1]	Soil evaporation	Interception	Runoff	Irrigation threshold[2]	Minimal irrig. amount
Surface	1.15	open canal: sand 0.7, loam 0.75, clay 0.8	unrestricted	no	surface, lateral, percolation	C4: 0.7 C3 (prec <900): 0.8 C3 (prec≥900): 0.9 Rice: 1.0	1 mm
Sprinkler	0.55	pipe: 0.95		yes	lateral, percolation		
Drip	0.05		soil evap. of irr. water reduced by 60%	no	none, only indirect precip. leaching		none

[1]Open-canal conveyance efficiency depends on soil hydraulic conductivity (K_s): $K_s > 20$: sand, $10 \leq K_s \leq 20$: loam, $K_s < 10$: clay; 50% of conveyance losses are assumed to evaporate, for loam and clay (higher K_s) and open canal conveyance the fraction is 60% and 75%, resp.; [2]depending on crop type.

Daily GIR and HIL add up to the total withdrawal request in each cell. This demand is met from local surface water, including reservoir water and if not sufficient, requested from neighboring upstream cells (Figure 2.2 and Biemans et al. 2011). Actually withdrawn irrigation water is always reduced by conveyance losses.

Irrigation scheduling is simulated to be controlled by $prec$ and the irrigation threshold (it), which defines the allowed degree of soil water depletion prior to irrigation. In sensitivity analyses we found that it is dependent on the CFT. C4 crops (maize, tropical cereals, sugarcane) are less sensitive to drought stress, because in contrast to C3 crops, they use a more efficient enzyme on the pathway of CO_2 fixation (Amthor 1995). The maximum yield for C4 crops is at $it = 0.7$ (global median, Figure A.3). Values of it for C3 crops (0.8–0.9) are found to be affected by annual $prec$; paddy rice is always parameterized with $it = 1$ (Table 2.1). Available irrigation water is reduced by available precipitation and the amount that is not released (if $S > it$, see Figure 2.2) is added to $Store$ (model-internal compensation for local water availability) and kept available until the next irrigation event.

Surface and drip systems are simulated to apply irrigation water below canopy, and sprinkler systems above-canopy with associated interception losses:

$$I = PET \times pt \times min(1, wet) \times f_v, \tag{2.10}$$

where pt is the Priestley-Taylor coefficient (1.32), f_v is the fraction of vegetated soil cover, and wet is fraction of the day with wet leaf surface, calculated as:

$$wet = \frac{min(1, intc \times LAI) \times (W_i)}{PET \times pt}, \tag{2.11}$$

where $intc$ is a CFT-specific interception storage parameter (Gerten et al. 2004).

Droplet evaporation with sprinkler systems, presumably <1.5% of the applied water (Meyers et al. 1970; Rogers et al. 1997), is implicitly accounted for. Furthermore, we restrict surface runoff for sprinkler systems, such that irrigation water that reaches the soil surface infiltrates and can only run off laterally or percolate into deeper layers.

We design drip systems, in contrast, with a loss-free infiltration into the first two soil layers, i.e. no surface or lateral runoff are subtracted from W_i. Soil evaporation losses from drip systems (only blue water) are reduced by 60%, to account for its localized subsurface application of water (Table 2.1).

Table 2.2.: Irrigation system suitability by crop type. Biophysical and technical irrigation system suitability by crop type (CFT), based on Sauer et al. (2010) and Fischer et al. (2012).

Crop type (CFT)	Surface	Sprinkler	Drip
Temperate cereals (wheat, rye, barley)	x	x	-
Rice	x	-	-
Maize	x	x	-
Tropical cereals (millet, sorghum)	x	x	-
Pulses (field peas)	x	x	x
Temperate roots (sugar beet)	x	x	-
Tropical roots (cassava)	-	-	-
Sunflower	x	x	x
Soybean	x	x	x
Groundnut	x	x	-
Rapeseed	x	x	-
Sugarcane	x	x	-
Others (e.g. cotton, vine, coffee, citrus)	x	x	x
Pastures	x	x	-

2.3.4. Development of new input data set for grid-level irrigation system distribution

Currently, no sub-regional information on the global distribution of irrigation systems is available, which would provide the missing link to more accurate simulations of irrigation water requirements and performances. We therefore develop a new dataset of the global distribution of irrigation systems, for each grid cell and CFT (Figure 2.3). Country-level shares of irrigation systems can be associated with a series of socio-economic and biophysical factors. A comprehensive explanation of these patterns is beyond the scope of this study, and here we simply adopt national statistics from AQUASTAT (FAO 2014b). Each country is assigned the respective share of the three irrigation systems (Table A.1), which we further disaggregate to the grid cell and the CFTs through a decision tree approach, using the extent of irrigated areas by CFT (Porkka et al. 2016; Siebert et al. 2015) and an irrigation system suitability table. The CFT suitabilities for each irrigation system (Table 2.2) are determined based on restrictions due to soil type, the CFT-specific tolerance toward moisture depletion, the characteristic planting and harvesting techniques, the specific physical habit of the crop, and its economic market value (e.g. low market value crops are excluded from drip irrigation); based on Sauer et al. (2010) and Fischer et al. (2012). The distribution of irrigation systems is adjusted annually (see Appendix A.2 for further details).

2.3.5. Simulation protocol

For this study, we ran LPJmL for the time period 1901–2009, forced with the Climate Research Unit's (CRU) TS 3.1 monthly climatology for temperature, cloudiness and wet days (Harris et al. 2014) and with the Global Precipitation Climatology Centre's (GPCC) precipitation data (Version 5) (Rudolf et al. 2010). Transient runs follow a 120-year spinup (recycling the first 30 years of input climatology) to bring sowing dates into equilibrium, which are fixed during the simulation period after 1960. Spatially explicit global information on cropland extent is obtained from the MIRCA2000 land-use dataset (Portmann et al. 2010). The extent of areas equipped for irrigation from 1900–2005 is imported from Siebert et al. (2015), who provide an improved estimate of historic irrigation expansion with a total global extent of 306 Mha in 2005 (297 Mha in LPJmL, see Porkka et al. (2016)).

Water use for non-agricultural sectors, HIL, account for 201 km^3 in the year 2000 based on recent estimates by Flörke et al. (2013). Our baseline simulation assumes that irrigation water withdrawal is constrained by local, renewable water storage, i.e. there is no implicit assumption about contributions from fossil groundwater or diverted rivers. If not indicated otherwise, results are presented as 1980–2009 averages.

In addition to the current distribution of irrigation systems, we ran three synthetic scenarios (hereinafter: All-Surface, All-Sprinkler, All-Drip), in which it is assumed that each system is respectively applied on the entire global irrigated area, irrespective of system suitability for crop types (Table 2.2). These scenarios were developed to investigate the global performance of each system and to provide an estimate of the effect of irrigation system transitions, they do not represent feasible transition targets.

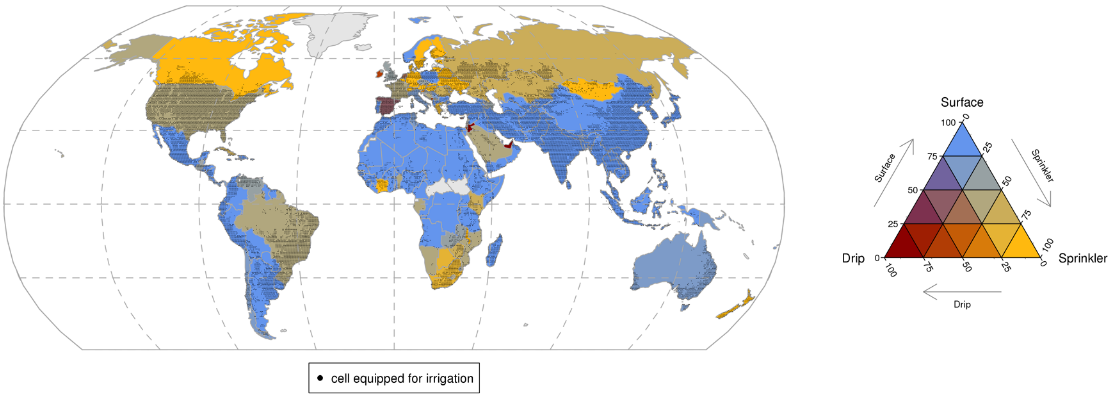

Figure 2.3.: Global distribution of irrigation systems at country level. Illustrated data are based on AQUASTAT statistics (FAO 2014b). Cells that include irrigated areas are hatched, based on Siebert et al. (2015).

2.4. Results

2.4.1. Global patterns of irrigation efficiency

51% of total global diverted irrigation water is simulated to be consumed (mean global area-weighted $E_i = 58\%$) and 26% are beneficially consumed, i.e. transpired (mean global area-weighted $E_b = 33\%$), following our process-based implementation. In Figure 2.4 we show global spatial patterns of E_b, which are to a large extent determined by the irrigation system in use (Figure 2.3), but as importantly, by its performance under local biophysical conditions and the present crop type. Extensive regions in Central, South, and South-East Asia with high shares of surface irrigation (widespread rice cultivation) show low efficiency values of <30%. North China plains with high irrigation intensity and mainly maize and wheat varieties exceed 50%, but particularly Europe and North America stand out with values well above the global average due to relatively high shares of sprinkler and drip systems. The latter also applies to Brazil, South Africa and the Ivory Coast, where E_b exceeds 60%. To illustrate system performances unaffected by their current geographical distributions, Figure 2.5 displays E_b for the three irrigation systems separately, each assumed to be applied on all irrigated areas. Under this condition, global average values of E_b for surface, sprinkler and drip systems are 29%, 51%, and 70%, respectively. Across all three scenarios, we find a remarkable low efficiency in Pakistan, North-East India and Bangladesh, opposed to above-average levels in the Mediterranean region, North China Plains and the US Great Plains. Moreover, E_b varies considerably between crop types due to different plant physiology and different cultivation regions

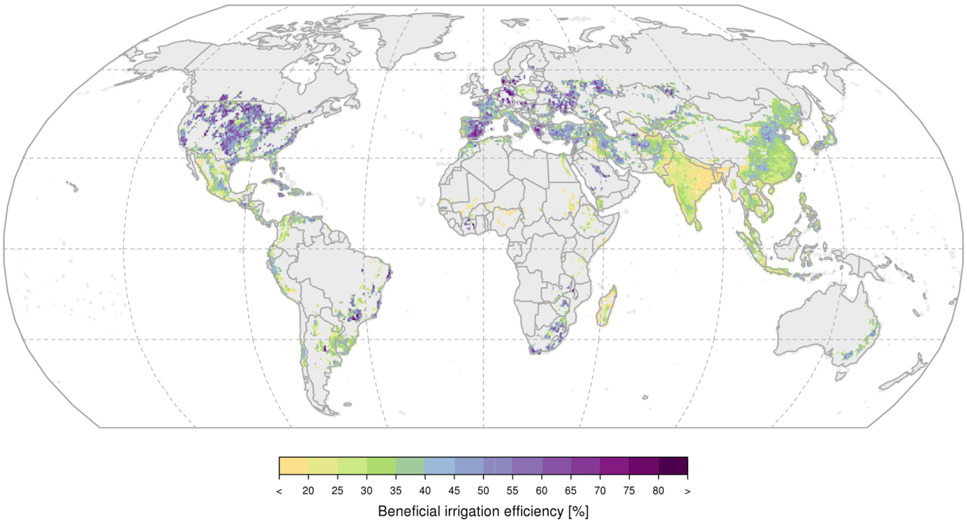

Figure 2.4.: Global patterns of beneficial irrigation efficiency. Beneficial irrigation efficiency (E_b) is the ratio of transpired and diverted water, shown as area-weighted mean over CFTs (exclusive "others" and pastures) and based on the system distribution in Figure 2.3.

and climate zones (Figure 2.6 and Section 2.4.2). The values for maize, sugarcane and temperate roots are above the average across CFTs in our simulation, while rice, pulses, and rapeseed form the lower end. E_b is also sensitive to precipitation, soil properties and other biophysical factors, as characterized in Section 2.4.4. We provide an online versions of global patterns of beneficial irrigation efficiencies (illustrated in Figure A.2) as gridded input for other studies.

2.4.2. Global irrigation water fluxes

Global irrigation water withdrawals simulated with our newly developed, process-based irrigation scheme are 2469 km^3 per year, averaged for the time period 2004–2009. 1212 km^3 return to the river system, while 1257 km^3 are consumed (1458 km^3 including consumption from non-agricultural sectors HIL), of which 649 km^3 are beneficially consumed, i.e. transpired by crops (Table 2.3). The remainder, 608 km^3, is non-beneficially consumed and is indicative of the substantial water saving potentials associated with irrigation improvements (see Section 2.4.3 for details).

Figure 2.6 illustrates the decomposition of irrigation water fluxes for each CFT and all three irrigation systems. Transpiration is relatively constant across irrigation systems (irrigation target).

Table 2.3.: Total annual sums of irrigation water fluxes. Annual sums (km^3) of irrigation water withdrawal (W_d), return flow (W_r), irrigation water consumption (W_c) that is further split into beneficial (W_{bc}) and non-beneficial consumption (W_{nbc}), and global mean E_b (average across irrigated cropland, in %), are shown as 2004–2009 averages. Columns separate the actual situation from the All-Surface, All-Sprinkler and All-Drip scenarios.

	Actual	All-Surface	All-Sprinkler	All-Drip
Withdrawal, W_d	2469	2741	1537	877
Return flow, W_r	1212	1411	520	110
Consumption, W_c	1257	1330	1017	767
Beneficial consumption, W_{bc}	649	651	665	605
Non-beneficial consumption, W_{nbc}	608	679	353	162
Beneficial efficiency, E_b	33	29	51	70

However, on a global average, drip systems achieve 9% less transpiration compared to sprinkler systems (beneficial consumption, Table 2.3). This result reflects that drip irrigation systems generally do not aim to saturate the soil and thus conduct a modest form of deficit irrigation not designed to maximize yields but to save water.

Return flow with surface irrigation forms the major part of non-beneficial fluxes, exceeding by a factor of two the non-beneficial consumption (evaporation from soil and water surfaces). Sprinkler systems have a considerably lower return flow fraction (34% of withrawal), which further declines with drip systems (13% of withrawal), and is here smaller than the fraction of non-beneficial consumption (Table 2.3 and Figure 2.6). Conveyance losses are significantly lower with sprinkler or drip systems due to pressurized conveyance. Evaporation losses are relatively similar between surface and sprinkler systems, while drip systems show lower losses due to their system design. Interception losses with sprinkler systems (surface and drip apply water below canopy) form only a minor contribution to non-beneficial fluxes (Figure 2.6).

2.4.3. Potential of irrigation system transitions

We simulated three theoretical “all-one-type” scenarios to investigate the global potential of irrigation system transitions. Replacing a surface system by sprinkler or drip systems could, on average, reduce the target value — non-beneficial consumption — by 54% and 76%, respectively, while maintaining yield production at the global level (indicated by W_{bc} in Table 2.3). Withdrawal amounts would decrease by 44% and 68%, and return-flows by 63% and 92%, respectively.

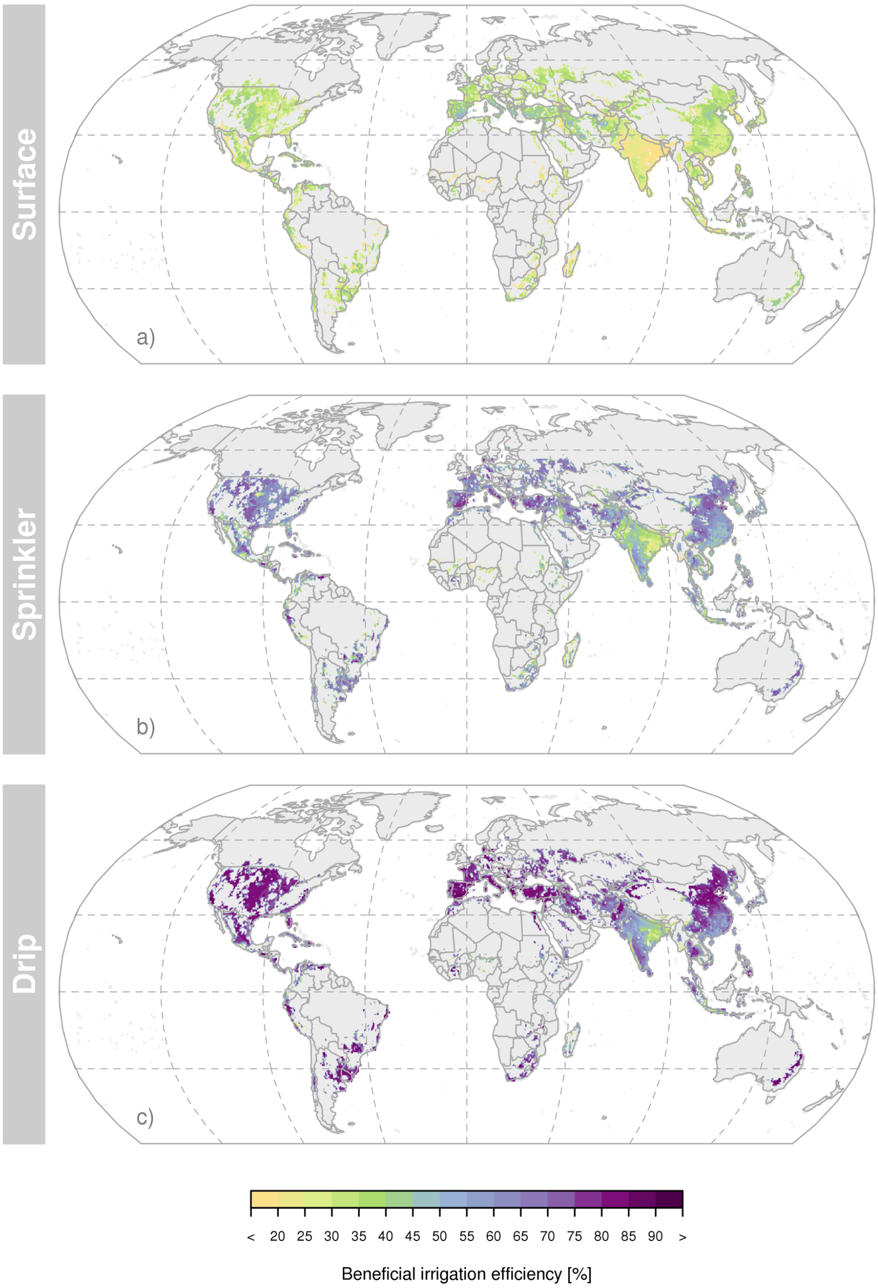

Figure 2.5.: Global patterns of beneficial irrigation efficiency for each irrigation system. Panels relate to (a) surface, (b) sprinkler, (c) drip systems, calculated as area-weighted mean over CFTs (exclusive "others" and pastures). This figure is based on theoretical scenarios, in which each system is respectively assumed to be applied on the entire irrigated area (see Section 2.3.5).

Table 2.4.: Global water saving and water productivity potentials with irrigation transitions. The table shows mean basin-level changes in non-beneficial consumption (W_{nbc}) and crop water productivity (CWP) through system transitions from surface to sprinkler and drip, respectively; area-weighted means over all simulated basins in %.

	Surface to Sprinkler	Surface to Drip
Change in W_{nbc}	-54 ($\pm$8)	-76 ($\pm$7)
Change in CWP	9 ($\pm$6)	15 ($\pm$10)

While upgrades of irrigation systems thus appear to be beneficial locally and mostly easing water diversion, major reductions of return flows can also have negative local impacts on downstream users. To evaluate the net effect along rivers and identify river basins that are most sensitive to irrigation improvements, we assessed water saving potentials and changes in water productivity at river basin level for each transition scenario.

Currently, the ratio of non-beneficial consumption to total consumption is particularly high in some South Asian basins (Indus, Ganges, Mahanadi), Korea, the Sahel, and Madagascar (Figure 2.7a). A transition from surface to sprinkler or drip systems is simulated to cause a distinct reduction in non-beneficial consumption mainly in these regions, but also in temperate regions in Europe, North America, the Yangtze basin, Brazil, Argentina and South Africa (Figure 2.7c,e). Mean basin-level reductions in non-beneficial consumption would amount to 54% when moving from surface to sprinkler systems and 76% when moving to drip systems (Table 2.4).

Current global mean water productivity is simulated to be 2.83 $kcal\ l^{-1}$, but with very distinct regional patterns (Figure 2.7b) due to a combination of many factors, mainly heterogeneous crop management intensities and current distribution of irrigation systems. We find a strong gradient from very low values ($<2\ kcal\ l^{-1}$) in Central America, Sub-Saharan Africa and South Asia, to medium levels in East Asia and high values of $\sim$4–5 $kcal\ l^{-1}$ across North America and Europe. Replacing a surface system by a sprinkler or drip system would increase crop water productivity by (globally averaged) 9% and 15%, respectively (Table 2.4). In individual basins, e.g. in extensive regions in Central and South Asia, Mediterranean region and the Nile, in the Sahel, in South Africa and in the Colorado basin, effects would be even more pronounced: at basin level production increases of $\sim$20% (sprinkler) and $\sim$30% (drip) would be attained (Figure 2.7d,f).

Moreover, we show explicitly that transpiration and total water consumption do not form a one-to-one relation, as is often argued when discussing the potential of irrigation transitions (e.g. Perry

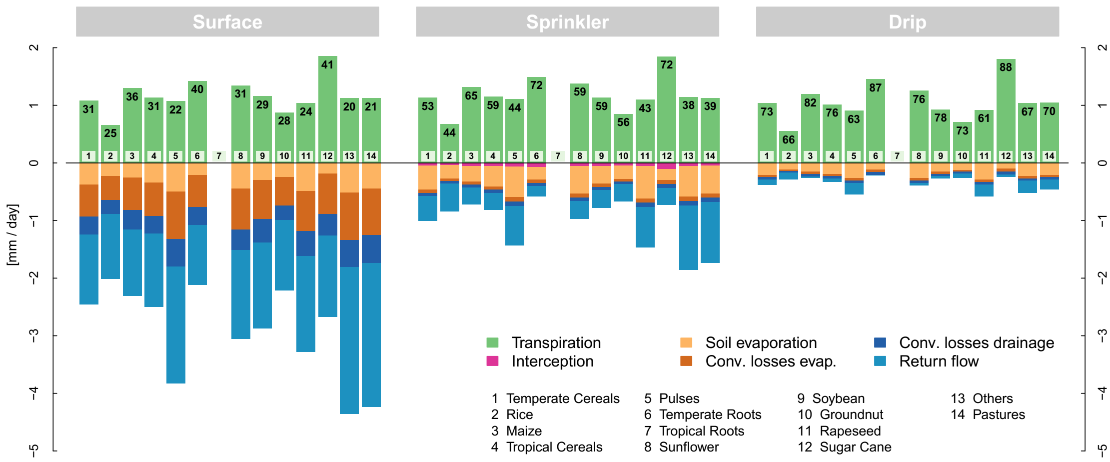

Figure 2.6.: Decomposition of beneficial and non-beneficial irrigation water fluxes for each simulated CFT and irrigation system, in mm/day averaged over the respective growing seasons and cultivated areas. For better comparability, each system is individually applied on all irrigated areas assuming the same, optimal management. The number at the top of each stack represent the CFT-specific beneficial irrigation efficiency (E_b, in %). Tropical roots are not irrigated.

et al. 2009). Surface, sprinkler or drip systems follow individual slopes, disclosing saving potential (Figure 2.8). Overall, this pilot analysis of irrigation system transitions shows that water saving potentials and water productivity improvements could be significant in many regions, on local farms and across basins.

2.4.4. Evaluation of simulation results

Our estimates of global irrigation water withdrawal and consumption (W_d: 2469 km^3, W_c: 1257 km^3) agree well with previously published, but not always state-of-the-art estimates. Country statistics for W_d reported for the period 1998–2012 are 2722 km^3 (FAO 2014b), while model estimates range between 2217 and 3185 km^3 (Wada and Bierkens 2014; Döll et al. 2014; Siebert and Döll 2010; Wada et al. 2011; Alexandratos and Bruinsma 2012; Döll et al. 2012). Estimates for W_c range from 927 to 1530 km^3 (Hoff et al. 2010; Chaturvedi et al. 2015; Döll et al. 2014). Döll et al. (2012) concludes that 1179 km^3 (Wada and Bierkens 2014, 1098 km^3) stem from surface water and an additional 257 km^3 from groundwater resources. This is supported by Wada et al. (2012), who also point out that non-renewable groundwater abstractions are expected to contribute $sim20\%$ to the global GIR. In this study we did not account for fossil groundwater and desalination. However, 80%

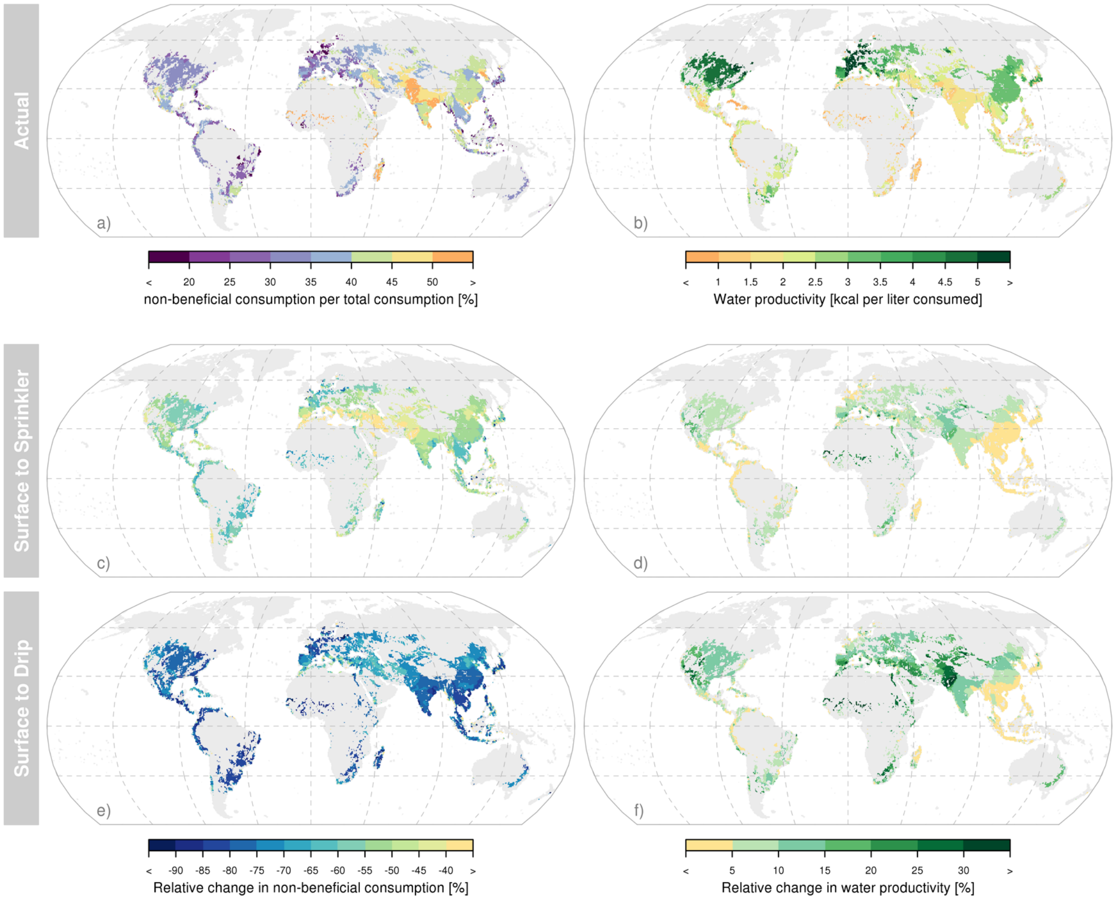

Figure 2.7.: Global patterns of potential changes in water productivity and non-beneficial consumption. Basin-level aggregation of ratio of non-beneficial consumption and total consumption (RNC, a), and water productivity (kcal from irrigated crops per consumed liter of blue and green water, b) given the current distribution of irrigation systems. Panels (c)–(f) show the relative change in E_b and water productivity given a transition from surface to sprinkler (c,d) and surface to drip systems (e,f), respectively (All-surface, All-sprinkler, and All-drip scenarios). Pastures and "others" are excluded.

of groundwater abstractions are assumed to be recharged by return flows (Döll et al. 2012), thus it is plausible that W_d as simulated here is somewhat lower than in studies that simulate (fossil) groundwater contributions. It is also important to point out that irrigation water estimates are sensitive to the precipitation database employed (Wada et al. 2014).

Irrigation efficiencies are difficult to validate due to nonhomogeneous definitions and problems in its measurement in the field. Nevertheless, in Table 2.5 we put our results into the context of comparable literature results. At the global level, we meet established indicative estimates of field application efficiency by Brouwer et al. (1989). These have been downscaled to the country level by Rohwer et al. (2007) and the area-weighted global mean is 49%, 69%, and 90% for the three systems, respectively. Another independent estimate of field efficiency at the sub-continent level is provided by Sauer et al. (2010) with global mean values of 42%, 78%, and 89%. Our estimates are well in line with these numbers, although some regional patterns from Sauer et al. (2010) are not represented in our results (Table 2.5). They find very low surface irrigation efficiencies in Middle East and North Africa (MENA) and Sub-Saharan Africa (SSA), while we arrive at slightly above-average values in MENA and particularly low values in South Asia, which is supported by Döll and Siebert (2002) and Rosegrant et al. (2002). For Malaysia, e.g. Hazrat Ali et al. (2000) confirms below-average values. Furthermore, our estimates of global water productivity agree very well with previous estimates (e.g. Brauman et al. 2013; Zwart and Bastiaanssen 2004; Rosegrant et al. 2002). Overall, the performance of our new irrigation model is well in line with the patterns reported in previous studies (while being much more detailed in terms of process representation, spatial and temporal patterns), rendering this implementation operational.

With Figure A.4 we can show that mechanistically simulated irrigation water fluxes (and thus efficiency patterns) follow expected biophysical dependencies. We are able to fit significant empirical relations between components of the irrigation water balance and biophysical explanatory variables, although each component is affected by interlinked processes and input variables, which themselves exhibit spatio-temporal patterns (e.g. local climatic conditions, crop type, crop phenology, LAI, length of the growing season, soil parameters). For instance, return flow mainly depends on $prec$ and WHC; WHC is more relevant for surface systems, while $prec$ appears to be most decisive for drip systems. Aboveground biomass affects soil evaporation negatively and interception losses positively. Precipitation during the growing season can lead to leaching of soil water that originated from irrigation, which can oppress efficiency indicators. Accordingly, Figure A.4 adds confidence that the newly implemented parameterization of irrigation systems in LPJmL is reasonable from a biophysical perspective and, as importantly, it supports a main finding of this study: the performance of irrigation systems is clearly governed by local biophysical conditions.

Table 2.5.: Evaluation of simulated irrigation efficiencies. Comparison of field application efficiencies (for reasons of comparison, we employ here the traditional definition: consumed per applied irrigation water) for major world regions compared with literature values in %. This study's results are area-weighted averages, based on current distribution of irrigation systems (see Figure 2.3).

World region	Surf	Sprink (this study)	Drip	Surf	Sprink (Rohwer et al. 2007)	Drip	Surf	Sprink (Sauer et al. 2010)	Drip
North America	53	77	86	49	68	90	50	85	93
South America	54	80	86	51	68	90	38	75	88
Europe and Russia	53	80	89	52	72	90	52	86	93
Mena	62	88	93	49	69	90	22	60	80
SSA	50	71	88	54	75	90	28	64	82
Central and East Asia	54	79	83	48	68	90	42	79	89
South Asia	48	83	90	48	68	90	32	68	84
SE Asia and Oceania	49	68	85	48	70	90	38	75	88
World	52	78	88	49	69	90	42	78	89

2.5. Discussion

2.5.1. Significance of results

This study presents for the first time spatially and temporally explicit estimates of irrigation system performances (separately for the world's major crop types) at the global level, based on process-based simulation of underlying local biophysical conditions. Hence, this study advances the global quantification of irrigation systems while providing a framework for assessing potential future transitions in these systems as likely required in view of projected increases in world food demand. Our global irrigation water estimates and regional efficiency values are well in line with existing literature, but we find distinct spatial patterns that were not available before with such level of spatial, temporal, and process detail. Generally, it has been assumed that economic and agronomic drivers control spatial patterns of irrigation efficiencies (e.g. Sauer et al. 2010; Schmitz et al. 2013). Here we show that biophysical factors additionally have non-trivial effects on spatial patterns of system efficiencies.

Moreover, we show that enhanced irrigation techniques offer substantial opportunities to reduce irrigation water consumption while maintaining beneficial transpiration rates and, thus, crop production levels at the river basin level. We also identify river basins in South Asia, in the

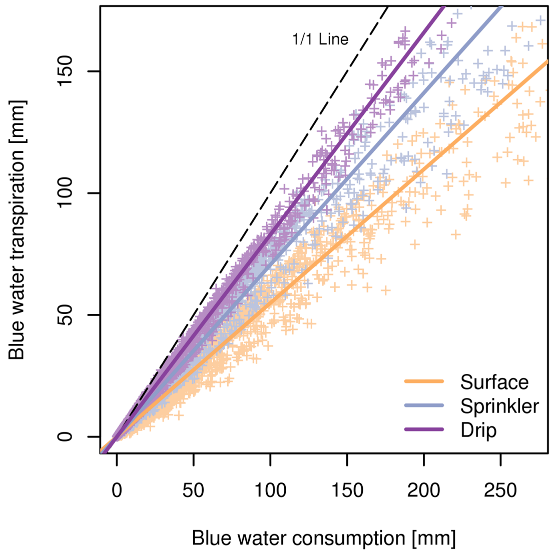

Figure 2.8.: Relation of blue water consumption and blue water transpiration. This ratio is shown for the three scenarios All-Surface, All-Sprinkler, All-Drip and each grid cell, compared to the 1/1-Line.

Mediterranean region, and the Sahel to be most sensitive to irrigation improvements as resulting from the combination of local crop types, climate and soil conditions and the current irrigation system. These findings contribute to the current debate on global opportunities associated with irrigation systems and results suggest that irrigation improvements are an important contribution to sustainably increase food production (among various other means, e.g. Kummu et al. (2012) and Jalava et al. (2014)). The new implementation is a prerequisite for follow-up studies of global crop production and yields under changing climate, production potentials of irrigation system transitions and expansions, and climate change impacts on irrigation efficiencies and demands.

2.5.2. Modeling issues

Previous LPJmL estimates of W_d and W_c (Rost et al. 2008b; Konzmann et al. 2013) are now improved with this study. Those earlier estimates tended to be lower than comparative studies, because first, the extent of irrigated land was scaled down for reasons of multi-cropping (see Fader et al. 2010, for details). Second, we believe that the new implementation accounts for a more realistic simulation of irrigation fluxes and the soil water balance, which on the one hand increases water demands, and on the other hand improves discharge dynamics, in that applied irrigation water percolates through soil layers and runoff rates are more realistically delayed.

Generally, not all of the area equipped for irrigation is being irrigated every year, especially where supplementary irrigation is practiced. Such deficits can be considerable, mostly in temperate and humid regions (Siebert and Döll 2010; Siebert and Ewert 2014). We claim that they are mostly considered in our simulations as it is a key component of our irrigation module to dynamically trigger or pause the application of irrigation water based on soil water deficit and blue water availability. However, variations in irrigated area due to other reasons (not reflected in the land-use input dataset) cannot be accounted for.

Validation of the new map of subnational distribution of irrigation systems remains a challenge until independent data of such becomes available at a large scale. Nonetheless, regional patterns are in accordance with national statistics and the recent literature, as our map is based on FAO country shares and explicit locations of irrigated cropland (Section 2.3.4). The reliability of our subnational distributions is strengthened across smaller countries (one national value controls a smaller area). But since irrigation efficiencies are generally better documented than the distribution of irrigation systems, we oppose efficiency values simulated in this study with published local and regional studies (Section 2.4.4). Irrigation efficiencies depend to a large degree on the geographical distribution of irrigation systems.

The CFT group “others” pools a variety of crops including perennial and annual types (e.g. cotton, citrus, coffee) but is generically parameterized as perennial grassland. Therefore, the growing season length for these crops is systematically overestimated, which may lead to somewhat too high estimates of total water use and demand. This potential overestimation might be counterbalanced by an overestimation of accessible return flow, as LPJmL cannot account for the fact that return flows are only partly recoverable (physically or economically), and that they are often degraded through nutrient leaching and salinity.

Irrigation can have other purposes than satisfying crop water requirements, like salt leaching, crop cooling, pesticide or fertilizer applications, or frost protection. These irrigation applications are however beyond the scope of this study and are not explicitly considered in the withdrawal demand. Salt leaching below the root zone, as for the most significant of those, is critical in regions with marginal precipitation and can be controlled through applying an additional 5–10% irrigation water (Jensen 2007). Figure 2.6 shows that in our implementation the runoff share with drip irrigation is, on average, large enough to meet this requirement.

Irrigation improvements can also be achieved by means other than completely replacing the system, e.g. through better scheduling (incorporating climate and soil data to precisely meet crop water demand), advanced management (deficit irrigation) and technical improvements. For instance, much water might be saved from evaporation and seepage if open canal conveyance systems were replaced by lined or pressurized installations. For the purpose of simplicity, in this study we bundle these various opportunities into the three different simulated generic systems and represent improvements through system transitions.

2.5.3. On irrigation system transitions

From a sustainability perspective, the primary objective in regions with irrigation overdraft is the reduction of irrigation water consumption. In face of a growing human population and various rapidly approaching planetary boundaries (Steffen et al. 2015), an immediate question thus is, by how much global crop water productivity and crop production can be improved with sustainably available water resources. Water saved through improved irrigation systems could allow either for an expansion of irrigated areas or for a production increase on irrigated yet water-limited farms. Throughout this paper we argue that the water saving potential is mostly constrained to the non-beneficially consumed fraction, as return flows are often accessible downstream. Egypt's Nile valley is an example of a multiple use-cycle system with a high basin-level efficiency but low local efficiencies (Keller and Keller 1995).

Many authors thus argue that irrigation efficiencies add up close to 100% at the basin level and therefore assume that water saving potentials through efficiency improvements are very limited (Seckler 1996; Perry et al. 2009; Frederiksen and Allen 2011). These findings are based on an assumption that crop transpiration follows a one-to-one relation with water consumption (Perry et al. 2009); saving potentials within the consumed fraction are largely neglected. Herein, we show that transpiration and consumption are not as closely linked as previously assumed, and that adapting modern irrigation techniques can indeed bring this dependency closer to the one-to-one line (Figure 2.8). Accordingly, we show that transpiration rates (hence crop production) can be maintained while cutting the consumed volume in many regions at the basin level.

However, the implementation of such technical water saving potential does not imply that necessarily less water would be diverted. Farmers' decisions are often driven by maximizing their return and rarely by environmental concerns; if they pursue efforts to save water, they often use it to expand their irrigated areas or shift to higher value crops, rather than loosing water allocations (Ward and Pulido-Velazquez 2008; Perry and Hellegers 2012; Pfeiffer and Lin 2014; Shah 2014). From a food security perspective, however, irrigation improvements drive water productivity and thus increase gross crop yield, consuming the same amount of water.

Nevertheless, increasing irrigation systems at the global scale while respecting sustainability boundaries, requires a complex combination of substantial investments, institutional water policy regulations, and cultural changes. Intelligent water pricing (currently rarely reasonable) is for instance a measure to achieve trade-offs at basin level through economic incentives (e.g. Molden 2007; Molle and Berkoff 2007; Ward and Pulido-Velazquez 2008).

Higher technology irrigation systems can have manifold co-benefits, e.g. improved crop quality, conserving nitrate groundwater concentration, reducing water logging, saving energy, and reducing greenhouse gas emissions (e.g. Gleick et al. 2011; Christian-Smith et al. 2012; Calderón et al. 2014). Low-cost drip systems for smallholder farmers can help alleviate poverty in poor regions (e.g. Postel et al. 2001; Kijne et al. 2009; World Bank 2010; Dillon 2011; Burney and Naylor 2012). They can boost water productivity, but are likewise prone to misuse and salinization (Belder et al. 2007; Hillel 2008; Comas et al. 2012).

Overall, this study suggests that the potential of irrigation improvements might be more substantial than often anticipated in recent discussions. Nonetheless, such investments should be combined with other measures available to sustainable intensification (e.g. mulching, reduced tillage, and rain-water harvesting).

2.6. Conclusions

This study presents for the first time spatially and temporally explicit estimates of global irrigation system performances for the world's major crop types, based on process-based simulation of underlying local biophysical conditions. Hence, this study significantly advances the global quantification of irrigation systems while providing a framework for assessing potential future transitions in these systems. We arrive at an estimate of global annual irrigation water withdrawal of 2469 km^3 (2004–2009); irrigation water consumption is calculated to be 1257 km^3, of which 608 km^3 are non-beneficially consumed. We find distinct spatial patterns in irrigation efficiency governed by biophysical conditions, which have been largely neglected in most previous studies. This new map of irrigation efficiencies is provided for incorporation into other global hydrological and agricultural studies, serving as a prerequisite e.g. for refined simulation of crop yields under conditions of future climate change and growing food demand. At the river basin level, i.e. accounting for downstream effects, we reveal, for many basins, the potential for sizeable reductions in non-beneficially consumed water (54–76%) and related significant increases in crop water productivity (9–15%) through transitions from surface to sprinkler or drip systems. These findings clearly suggest that irrigation system improvements should be considered an important means on the way to sustainable food security.

2.7. Author contribution

J.J. designed the study, developed the model code, and performed the simulations. D.G. contributed to study design. J.H. and S.S. contributed to code development. M.K. prepared land-use input data. J.J. prepared the manuscript. D.G., W.L., and M.K. contributed to manuscript preparation.

2.8. Acknowledgements

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Chapter 3.

Toward a revised planetary boundary for consumptive freshwater use: role of environmental flow requirements

An edited version of this chapter has been published in the journal *Current Opinion in Environmental Sustainability*[1]:

D. Gerten, H. Hoff, J. Rockström, J. Jägermeyr, M. Kummu, and A. V. Pastor. 2013. "Towards a revised planetary boundary for consumptive freshwater use: Role of environmental flow requirements." *Current Opinion in Environmental Sustainability* 5 (6): 551–558. doi:10.1016/j.cosust.2013.11.001

[1]Featured in the special issue *Aquatic and Marine Systems*, edited by Charles J. Vörösmarty, Claudia Pahl-Wostl, and Anik Bhaduri.

3.1. Abstract

We review the conceptual and quantitative foundation of the recently suggested "planetary boundary" for freshwater (PB-Water; i.e. tolerable human "blue" water consumption), and propose ways forward to refine and reassess it. As a key element of such a revision we suggest a bottom-up quantification of local water availabilities taking account of environmental flow requirements. An analysis that respects these requirements in a spatially explicit manner suggests a PB-Water of ~2800 km^3/yr (the average of an uncertainty range of 1100–4500 km^3/yr). This is notably lower than the earlier suggestion based on a simpler top-down analysis (4000 km^3/yr, the lower value of a range of 4000–6000 km^3/yr). The new estimate remains provisional, pending further refinement by in-depth analyses of local water accessibility and constraints up-scaled to the global domain, including study of cascading impacts on Earth system properties. With a current blue water consumption of >1700 km^3/yr, PB-Water is being approached rapidly. Thus, design opportunities to remain within PB-Water are imperative. We argue that their quantification requires analysis of tradeoffs with other planetary boundaries such as those for land use and climate change.

3.2. Introduction

The recently developed concept of "planetary boundaries" (PBs) (Rockström et al. 2009c) aims to identify environmental processes that regulate Earth system resilience and define boundaries of each process which, if exceeded, threaten the Holocene stability of the Earth system. Among the suggested nine PBs is the maximum amount of freshwater that can be appropriated by humans, beyond which there is a high probability of (possibly abrupt) water-induced changes with large detrimental impacts on human societies. This threshold was provisionally set at 4000 km^3/yr of global consumption of blue water (BW) from rivers, reservoirs, lakes and aquifers (Rockström et al. 2009c). While a specific level has not yet been set for the "green" water available in soils, a BW consumption of >4000 km^3/yr is deemed to "significantly increase the risk of approaching green and blue water-induced thresholds (collapse of terrestrial and aquatic ecosystems, major shifts in moisture feedback, and freshwater/ocean mixing)" (Rockström et al. 2009b). That is, simultaneous exceedance of some critical level of BW consumption rates in many locations may trigger large-scale impacts detrimental to Earth system functioning and human society. Notwithstanding existing uncertainties (Rost et al. 2008b), BW consumption by agriculture, households and industries is already about half the original estimate of PB for freshwater (hereinafter generically "PB-Water").

Global BW consumption was chosen as a proxy for PB-Water, as the BW amount (aggregated over a river basin) reflects the complex processes of precipitation partitioning into green water/soil moisture, BW and flow dynamics in the landscape.

Rockström et al. (2009c, 2009b) calculated PB-Water based on the upper limit of accessible global BW resources (~12,500–15,000 km^3/yr cf. earlier estimates). As only part of this water should be withdrawn to avoid deleterious environmental and social impacts due to water stress, PB-Water was set to 4000 km^3/yr, the lower limit of an uncertainty range of 4000–6000 km^3/yr. This calculation was based on lumped, global estimates of water availability, water stress and other processes that determine PB-Water, largely neglecting their spatiotemporal patterns. Flow requirements of aquatic faunal and floral habitat were treated as a global average only. To enhance the credibility of the preliminary estimate of PB-Water and to reassess it with more precision, we propose a bottom-up, spatially explicit and context-specific quantification of BW availability that, in particular, accounts for environmental flow requirements (EFRs) in river systems as a major determinant of PB-Water. On the basis of an ecohydrologic modelling framework, we provide spatially explicit estimates of EFRs and an accordingly modified, globally upscaled PB-Water.

Besides this analytical approach, we provide some perspectives on the conceptual development of PB-Water. We also suggest that a refined assessment of PB-Water should be linked to comprehensive assessments of societal water demands and potentials to improve water use efficiency (in the context of exploring "planetary opportunities" (De Fries et al. 2012)), in order to determine closeness to, and options to stay within, PB-Water.

3.3. Ecosystems set boundaries for human water appropriation

Apart from contributions from desalinated seawater, fossil groundwater and engineered water transfers, the maximum amount of freshwater available to humans is the precipitation over land. Governed by land surface and near-surface physical characteristics, precipitation is partitioned into evapotranspiration and runoff (which eventually forms cumulative river discharge), with temporary water storages in soils, shallow groundwater, lakes or reservoirs. In this context, it has been recognized that terrestrial and aquatic ecosystems are legitimate water users for the sake of maintaining the ecosystems themselves and their contribution to services that support human well-being (Falkenmark et al. 2004). Hence, PB-Water needs to consider the soil water and

BW amounts required for sustaining ecosystems as factors that place constraints on human water appropriation.

From a hydrological viewpoint, terrestrial ecosystems rely almost exclusively on soil water in the root zone (relative to atmospheric moisture deficit (Gerten 2013)), which itself is controlled by the physics of soils and vegetation. Hence, the water requirements of these ecosystems are affected more directly by climate and land use than by human water use. Nonetheless, they play an implicit role when conceptualizing PB-Water together with a PB for land use (see below).

In contrast, aquatic ecosystems in some sense must directly compete for BW with human demands to assure their integrity. The water requirements to sustain these ecosystems in a fair or good status (i.e. the EFRs) need to be respected in terms of total flux volumes, spatio-temporal patterns, and also water quality. Unfortunately, the volumes required to meet EFRs are already being tapped in many river systems worldwide (Smakhtin et al. 2004). They have previously been determined for a large number of case study regions, based on different, context-specific methods and different ecosystem protection or restoration targets (Poff et al. 2010). However, it is difficult to establish a uniform method for calculating EFRs across all river basins or for upscaling them to larger domains, as they depend on many environmental features (seasonal hydrograph, river geometry, river-floodplain interactions, climate, watershed properties). We propose that rivers be classified according to their flow regimes and associated EFRs, as an important step to revise PB-Water with sufficient precision in a bottom-up approach.

3.4. Quantitative assessment of EFRs and respective revision of PB-Water

In the following quantification, we use five hydrological EFR estimation techniques (to account for differences among methods) needed to sustain rivers in at least a fair ecological state, which are detailed in Pastor et al. (2014) and briefly summarized here. Three of these methods already exist (Smakhtin et al. 2004; Tessmann 1980; Tennant 1976), while two of them are newly developed. Tessmann's method (1980) allocates a percentage of mean monthly flow to EFRs, ranging from 40% during high flow seasons to 100% during low flow seasons. In each method, high (low) flows are denoted when mean monthly flow is larger (smaller) than annual mean flow. Tennant's method (1976) departs from mean annual flow, allocating 20% of it in low flow seasons and 40% in high flow seasons. Smakhtin et al.'s method (2004) allocates volumes representing the Q90 percentile as a base flow and an additional percentage of mean annual flow during high flow periods. The "Q90_Q50" method (Pastor et al. 2014) uses the Q90 quantile to allocate water to EFRs in low flow periods and the Q50 quantile in high flow seasons. The "Variable Monthly Flow" method (Pastor et al. 2014) allocates from 30% of mean monthly flow in high flow seasons to 60% of mean monthly flow in low flow seasons.

All methods were applied at a monthly step and the EFR estimates were aggregated to obtain average annual values for this study (years 1980–2009). Calculations on individual 0.5° x 0.5° grid cells (i.e. for the river stretches flowing through the cells), yielded spatially improved estimates compared to those made only at river outlets as in earlier analyses. We focus our presentation on the median and the maximum EFRs given by the five methods. We also assess anthropogenic flow modification by comparing discharge under potential natural vegetation (PNV simulation) with that under actual land use, irrigation and reservoir management (ACT simulation). All simulations are from the LPJmL dynamic global vegetation and water balance model (Rost et al. 2008b), driven by the CRU TS 3.10 climate dataset (Harris et al. 2014) and, for the ACT simulation, by data (for around year 2000) on the annual distribution of rainfed cropland and grazing land, irrigated cropland and managed reservoirs, as described in Biemans et al. (2011) and Fader et al. (2010).

Figure 3.1a and b reveals that BW availability has increased in many regions due to historic land use changes but has decreased in other regions due to irrigation and reservoir operation. Today, their collective impacts more or less cancel each other out at global scale, but regional differences are noteworthy. Consideration of EFRs would strongly reduce the total available BW, by 36% globally when using the median of different EFR calculation methods (Figure 3.1c) and by 57% when using the maximum of different methods (Figure 3.1d). Note that the median and maximum estimates were derived separately for each grid cell.

To refine the existing estimate of PB-Water based on these simulations, we adopt the basic calculation scheme put forward by Rockström et al. (2009c, 2009b). New estimates are presented in Table 3.1. We deviate from the original approach in three respects. First, we upscale the EFR component from the spatially explicit estimates at grid cell-scale described above. Second, we use a somewhat different estimate of BW availability (as simulated by LPJmL using the specified climatic data). And third, we adjust the original assumption on accessible BW volumes by the amounts of water that humans are currently able to store in reservoirs.

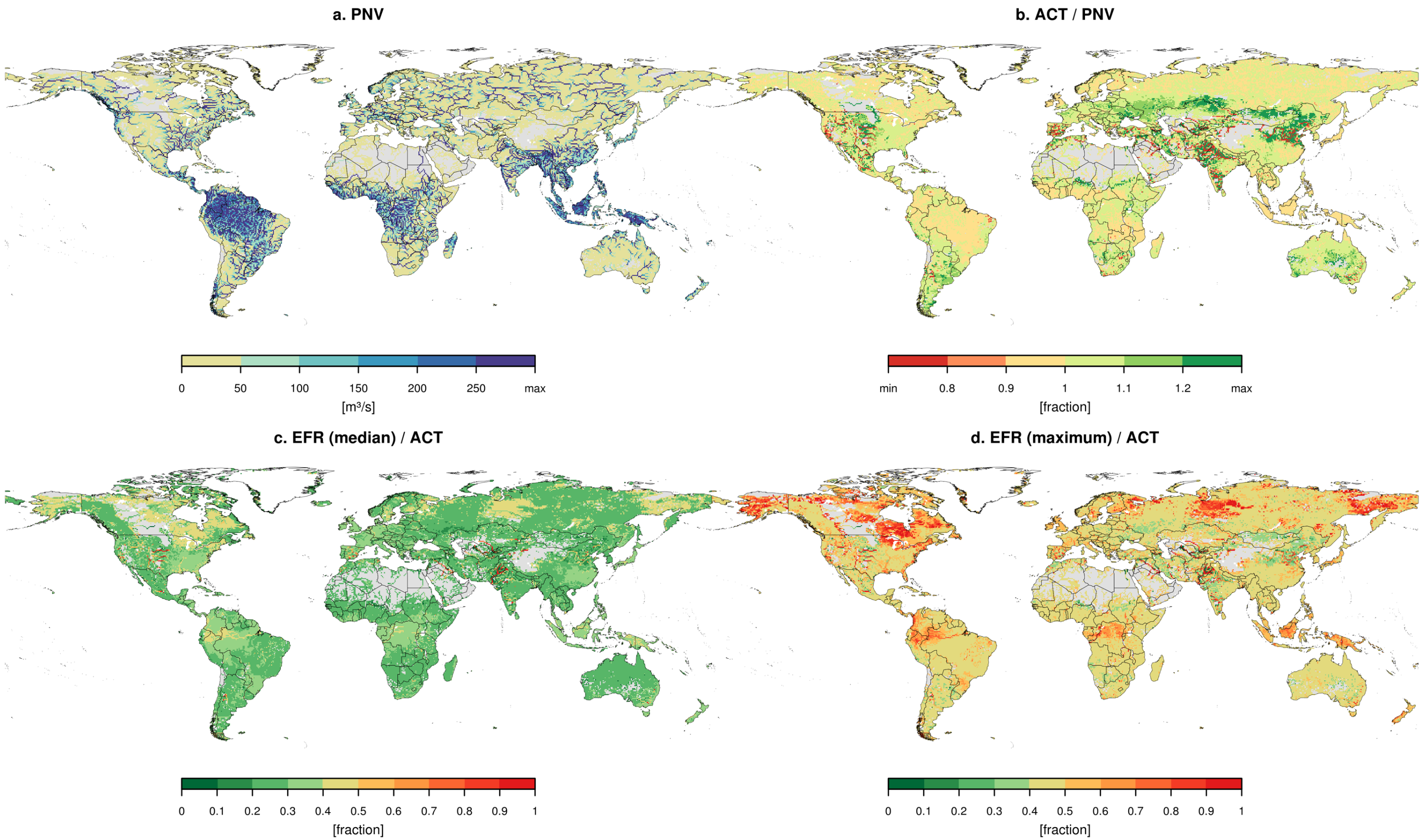

Figure 3.1.: Simulated river discharge and environmental flow estimates. Simulated river discharge (a proxy for blue water availability) and environmental flow requirements (EFRs) derived from different methods, averaged over the period 1980–2009. Discharge under “naturalized” conditions of potential natural vegetation in the catchments (PNV simulation) in $m^3\ s^{-1}$ **(a)**; change in discharge due to current land use, irrigation and reservoir operation (ACT simulation) relative to PNV **(b)**; and EFRs as fraction of natural discharge (median estimate of five methods, **(c)**; maximum estimate, **(d)**). White: lakes and ice; grey: regions with discharge $<1\ m^3\ s^{-1}$ where no EFRs were computed.

Primarily, on the basis of Postel et al. (1996), Rockström et al. (2009c, 2009b) restricted the global BW availability — taken to range between 39,700 and 42,800 km^3/yr with an assumed average of 40,700 km^3/yr (Tennant 1976) – to the fraction that humans can actually access, in that they subtracted discharge volumes that run off either in remote regions or as uncaptured storm flows. This left ~31% of the total global discharge, or 12,500 km^3/yr (Table 3.1). We continue to follow this simple approach out of necessity, as a spatially detailed quantification of accessible BW volumes is beyond the scope of this study (see discussion below). However, we increase the earlier global estimate of accessible BW by accounting for the significant volumes currently stored by dams and actively used in flow regulation (globally ~6900 km^3/yr (Postel et al. 1996)). This yields an accessible fraction of 39% of total global BW, equalling ~16,300 km^3/yr (Table 3.1).

Subsequently, Rockström et al. (2009b) considered that only up to 40% of this maximum accessible BW amount should be consumed, since a transgression of this threshold is commonly considered to result in physical water scarcity for humans and ecosystems (Falkenmark 1998). This restriction of BW already implies some assumption on the relative magnitude of a global EFR. Therefore, for our PB-Water computation we did not simply reduce the accessible BW resource by 60% but only by 30%, considering that the other 30%, that is, the global estimate of EFRs in Rockström et al. (2009c), represents a valuable rule-of-thumb value (Falkenmark et al. 2007)). In our analysis we thus deduct, as in Rockström et al. (2009c), a proportion of the available BW (half of 60%) to reflect the risk of physical water stress induced for reasons (e.g. related to maintenance of moisture feedback, wetlands and estuaries) other than breaching EFR levels (which primarily represent the BW needed to sustain aquatic ecosystem functions). We then calculate, based on our spatially differentiated analysis, new values of EFR (distinguishing medium and maximum EFR estimates as specified above). Furthermore, we consider an uncertainty range for BW availability and use, proposed to be 1000 km^3/yr following Rockström et al. (2009b), who set PB-Water at the lower end of this range, as do we (Table 3.1).

The resulting PB-Water lies between 1100 km^3/yr and 4500 km^3/yr, depending on whether a strict or a moderate assumption on EFRs is applied (Table 3.1). The average of these two estimates, that is, 2800 km^3/yr, is notably lower than the original estimate of 4000 km^3/yr (Rockström et al. 2009c), as proposed earlier (Molina 2009), suggesting that BW consumption may be closer to PB-Water than previously thought. This reflects the observation that large volumes of EFRs are already appropriated by humans (Smakhtin et al. 2004).

These provisional calculations reveal the complexity and uncertainties associated with defining PB-Water. Although the numbers presented above are based on high-resolution spatial patterns of BW availability and EFRs (highlighting the pronounced regional pattern of ecologically informed BW limitations), more sophisticated and consistent bottom-up analyses of governing processes and their uncertainties are necessary. Such a more comprehensive assessment should first and foremost revise Postel et al.'s (1996; 2013) global estimate of accessible BW resources (maximum 39% of total BW), especially since other authors assume higher fractions (up to 53% (Vörösmarty et al. 2005)). The accessibility will have to be assessed river by river; spatial datasets on the proximity, hence potential accessibility, of water resources to human populations (Kummu et al. 2011) are valuable for this purpose, enhanced by information on (fossil) groundwater. A related caveat is that many river reaches, such as in subarctic and inner-tropical regions, show high EFRs (see Figure 3.1c and d) but are sparsely populated. Thus, it is unlikely that EFRs are actually tapped in these regions, such that we may overestimate the global EFR constraint on BW consumption and underestimate PB-Water. Conversely, explicit consideration of possible local constraints to BW consumption other than EFRs (see below) may lead to somewhat lower PB-Water estimates.

In general, uncertainties in precipitation data, gauge data, and hydrological model formulations need to be accounted for in more sophisticated assessments in order to reflect the significant differences (± ∼20%, i.e. 42,000–66,000 km^3/yr (Haddeland et al. 2011)) in current estimates of global BW availability, which will propagate to the PB-Water estimate. Uncertainties in EFR estimates as considered herein are analysed in detail by Pastor et al. (2014). Besides, multi-annual averages can only be the first step in specifying freshwater availabilities and boundaries, given interannual hydroclimatic variability (Kummu et al. 2014) which influences seasonally variable EFRs (Hanasaki et al. 2008).

3.5. Land use and climate change effects on the freshwater boundary

The above section provides bottom-up estimates of EFRs as one element to refine PB-Water assessments and identifies some next steps in this direction. In this section we suggest that land use and climate need to be considered as well in PB-Water assessments (without being able to quantify the respective contributions, which is left for future study).

Table 3.1.: Calculation of the planetary boundary for freshwater. Blue water volumes in Rockström et al. (2009c, 2009b) original and this paper's calculation of the planetary boundary for freshwater. All values are in km^3/yr, rounded to nearest hundred. Numbers in bold represent the lower estimate from the applied uncertainty range, referred to in the text. This study's values are based on LPJmL simulations (1980–2009 average) using the CRU TS 3.10 climatology as input; areas covered with ice and open water bodies are excluded (see Figure 3.1).

	Rockström et al.	This paper
Total renewable BW resource	40,700	41,700
Accessible BW resource (subtracting remote and high flows)	12,500 (31% of total)	16,300 (39% of total)
Fixed fraction (60%) subtracted to respect EFRs and avoid water stress	5000	n.a.
Half of the fixed fraction, i.e. 30% (to reflect physical water stress factors other than EFR tapping) plus bottom-up EFR estimation (median and maximum of five methods)	n.a.	2100–5500
Ditto, applying the lower end of an uncertainty range of BW availability and use (±1000 km^3/yr, Rockström et al. 2009,2009a)	4000	1100–4500
Average based on medium and maximum EFR estimate	n.a.	2800

Land cover and land use influence BW availability through partitioning of incoming precipitation into (sub)surface runoff and evapotranspiration, thus constraining or increasing PB-Water in two major ways: through generation of runoff that sustains local and downstream river discharge, and through recycling of moisture that helps to regulate local and downwind precipitation (Ent et al. 2010). Evidence suggests that historic land cover and land use changes have increased discharge, sometimes substantially, over regional and continental domains (Douglas et al. 2006), and by ∼5% globally compared to a state without human impact (Gerten et al. 2008). Reservoir operation and irrigation of cultivated land have reduced global discharge to a similar degree (Biemans et al. 2011; Gerten et al. 2008) (also see Figure 3.1a and b). Regarding the effect of land cover on downwind precipitation, Ent et al. (2010) have provided an initial assessment of the dependence of different regions on precipitation originating from terrestrial evapotranspiration. Such work needs to be complemented by a dynamic representation of the hydrological effects of land use changes, in order to assess their consequences for (downstream) discharge and (downwind) precipitation alike. For instance, deforestation often decreases moisture recycling, whereas irrigation tends to increase it (Keys et al. 2012). Even if preliminary and not framed in a PB-Water perspective, current evidence thus suggests that regional and planetary water boundaries vary in time.

These boundary dynamics are due not only to land use changes, but also to other factors such as climate change, which if unmitigated will impose severe changes on the availability of BW and also soil moisture/green water (Gerten et al. 2011). Hence, any local change in water availability, and in EFRs, alters the respective boundary of environmentally and socially tolerable human water appropriation. Assessing PB-Water and its dynamics under conditions of socioeconomic and climate change, along with downstream and downwind impacts of land use change on green and blue water, remains a desideratum for future research.

3.6. Staying within interlinked water and land boundaries

Humanity's demand for water (and other resources) also changes continuously, and these dynamics determine the degree to which PB-Water (dynamic itself) is being approached. There was a marked global increase in BW consumption (and resulting water scarcity) particularly in the second half of the 20th century (Kummu et al. 2010). Wada et al. (2011) found that BW consumption increased by about 1000 km^3/yr in the four decades from 1960 to 2000, reaching 1831 km^3 in year 2000 (range of other studies for the 1995 to 2000 period, $\sim$1700–2270 km^3/yr (Shiklomanov and Rodda 2003; Hanasaki et al. 2010)). This value is already higher than the lower end of our uncertainty range of PB-Water. Further increases are expected for the future, both in terms of industrial and domestic water consumption (Alcamo et al. 2007) (if not leveling off when high technical standards are applied) and in terms of crop irrigation owing to growing food demand and climate change (Konzmann et al. 2013). Also, appropriation of soil moisture for crop growth would increase if more areas were dedicated to cropland or grazing land, while climate and CO_2 change will modify water availability and water use efficiency on such areas (Gerten et al. 2011). Indeed, exceedance of the PB for climate change, that is, greenhouse gas emissions levels leading to a global mean warming of more than $\sim$2 K above pre-industrial (Rockström et al. 2009c), would complicate matters. For example, associated precipitation declines — expected for many regions if climate change is unabated (IPCC 2008) — are likely to push local systems closer to their very freshwater boundaries while at the same time lowering these very boundaries. Measures to mitigate climate change, such as bioenergy production, involve substantial further appropriation of water and land (Beringer et al. 2011), which is but one reason why water, land and climate PBs need to be treated jointly (see Ringler et al. 2013, in same special issue as this article).

There are naturally various options to stay within local or global freshwater boundaries by reducing water demand and increase water use efficiency — among them consumption of less water-demanding products, changed diets, measures to close yield gaps, and reduction of food loss and waste (Kummu et al. 2012). If, for example, water (both green and blue) was used more effectively on present irrigated and rainfed cropland, more food could be produced (Molden 2007), although such measures are not sufficient alone to meet significantly higher food demands (Rost et al. 2009). Indeed, Foley et al. (2011) conclude that by combining different methods, food availability could be strongly increased without expanding agricultural land. One of these methods is to increase irrigation and expand irrigation areas; in that case, staying within the PB for land use will come at the expense of approaching PB-Water faster. If, however, those measures fail to be implemented and food waste is not reduced, the PB for land use will be approached more rapidly (assuming cropland expansion), which in turn would feed back to BW availability through mechanisms discussed above. In countries where arable land is limited and/or where the aforementioned options to stay within local freshwater boundaries are not feasible or are already fully exploited, more food may have to be imported from other regions (Fader et al. 2013), possibly pushing (water) systems in the export regions closer to their tolerable limits.

These examples emphasize the need to explore interdependencies of different PBs (Galaz 2012; Rockström 2012) and to frame a new PB-Water in the context of a (revised) PB for land use. There is also scope to analyse repercussions to the PB for terrestrial and aquatic biodiversity (likely to decline with land use change and tapping into EFRs), the PBs for nitrogen and phosphorus (if more fertilizers are required for agricultural intensification), and eventually the PB for climate change (more likely to be exceeded in case of additional carbon release from expanding cropland into forests). Spatially explicit understanding of interdependencies of PBs could also reveal options for tradeoffs and synergies among them.

3.7. Conclusions

We call here for a comprehensive assessment of PB-Water and its possible future evolution, starting from the present initial set of calculations and then using a spatially consistent framework that combines a bottom-up approach (based on an assessment of local EFRs as done here) with a top-down analysis (based on the functioning of the global water cycle in relation to other processes that govern Earth system resilience). There is an essential need to combine bottom-up and top-down approaches, because while some constraints on water use are local (i.e. EFRs) others operate over large domains up to the global scale (e.g. maintaining the hydrological cycle and dependent ecosystems). Another requirement is to link these biophysical analyses with social-ecological analysis in relation to development goals such as food security, water security and environmental sustainability.

This paper summarizes elements of a revised PB-Water — including a first quantitative amendment by means of spatial EFR estimates — and proposes ways forward to quantify it with state-of-the-art methods, including an analysis of tradeoffs and synergies with other PBs. Pending more comprehensive studies of this type, the current estimates of PB-Water, that is, 4000–6000 km^3/yr (Rockström et al. 2009c, 2009b) and, respectively, 1100–4500 km^3/yr (this paper), should be treated as provisional. In further studies, green water (soil moisture) also needs to be accounted for in relation to a PB for land use, because of its indirect human appropriation for terrestrial ecosystem services that go beyond direct appropriation of water for crop growth. Furthermore, macro-scale impacts that may occur if critical green and blue water thresholds are crossed synchronously in different regions (i.e. the lumped remainder of 30% BW reduction in the above analysis) require spatially detailed analyses as well, including an evaluation of the degree to which such impacts are still tolerable. Among these cascading macro-impacts are major droughts or desertification due to shifts in the hydrological cycle (owing to climate and/or land use change) and resulting in yield declines or even collapses of rainfed or irrigated agricultural systems (Rockström et al. 2009b). Furthermore, collapses of riverine, estuary, limnic and coastal ecosystems were identified as a possible consequence of excessive BW consumption or other forms of streamflow and lake level reduction. For example, a synchronized occurrence of droughts in several major crop-producing regions of the world (possibly induced by transgression of the PB for climate change (Cook et al. 2007)) may propagate through human societies' interconnected global networks, which might bring about collapses in food markets, famines, or mass migrations (Rockström et al. 2009b; Helbing 2013). A revised PB-Water needs to reflect such aggregated global impacts on earth system functioning, ecosystems and humanity, and to quantitatively link them to the crossing of local thresholds of water consumption and flow modification. We recommend that a resilience framework (Folke 2013) be used to develop a cross-scale methodology for defining a spatially consistent PB-Water while applying an analysis of water-induced thresholds of particular concern for landscape and biospheric stability.

Ultimately, quantifying planetary or local water boundaries is not enough. Equally important is an associated assessment and evaluation of local and global demand for water and other natural resources, together with a systematic exploration of opportunities to stay below the PB-Water. A bottom-up, newly constructed PB-Water will thus help to guide local or regional limits of water use (see e.g. the 'redline' water policies in China (Liu et al. 2013)) and context-specific opportunities for sustainable development.

3.8. Acknowledgements

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Chapter 4.

Reconciling irrigated food production with environmental flows in face of SDG implementation

This chapter, supplemented by Appendix B, is currently in revision at the journal *Nature Geoscience*. The author list is as follows:

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4.1. Abstract

Safeguarding river ecosystems is a precondition for attaining the UN Sustainable Development Goals related to water and the environment (SDGs) (Vörösmarty et al. 2010; United Nations 2015a), while rigid implementation of such policies may hamper achievement of other goals such as food security and poverty reduction. River ecosystems provide life-supporting functions that depend on maintaining environmental flow requirements (EFRs), but their global quantification remains difficult (Smakhtin 2008; Poff et al. 2010; Griggs et al. 2013). Here we establish process-based estimates of EFRs and their violation through human water withdrawals on a global 0.5° resolution grid, and we quantify the expected loss in food production if water use was to be constrained by EFRs. Our results indicate that 39% of current global irrigation water use (948 km^3/yr) occurs at the expense of water needed to sustain riverine ecosystems. 4.6% (13.9%) of global (irrigated) kilocalorie production depend on these volumes, and roughly half of irrigated cropland would face a ≥10% production loss if EFRs were to be maintained. Further results suggest that a moderate upgrade of irrigation systems could compensate for such losses on a sustainable basis in many regions, which supports implementation of the ambitious and seemingly conflicting SDG agenda.

4.2. Introduction

Global agricultural intensification through ever-increasing resource use is a main driver of current transgressions of "planetary boundaries", i.e. critical global and regional levels of anthropogenically influenced Earth-system processes such as land use change, biodiversity loss, freshwater use, and nitrogen and phosphorus loads (Steffen et al. 2015). Thereby the risk increases that the Earth system is transformed into a post-Holocene state with characteristics that potentially undermine system resilience and human welfare (Steffen et al. 2015). Because agriculture is central to attaining the renewed SDGs, they now acknowledge such risks by committing all countries to a bold and transformative agenda in support of the twin challenge: protection of Earth's life-support system while reducing hunger and poverty (United Nations 2015a). With the human population set to rise to 9 billion by 2050, the implementation of this vision aligned with environmental guardrails requires precautionary policies based on solid quantitative grounds such as formulated in the planetary boundary framework (Griggs et al. 2013). For progress monitoring, a global SDG indicator framework has been developed (ECOSOC 2016b), but proposed actionable specifications for environment-related indicators remain insufficiently advocated (Griggs et al. 2014; ECOSOC 2016b).

Freshwater resources, as a core example, are clearly over-exploited and aquatic ecosystems are thereby rapidly degrading in many regions (Vörösmarty et al. 2010; Molden 2007). Restoration of currently compromised river ecosystems through securing EFRs would thus entail a substantial reduction in water availability for irrigated food production, which is the largest global freshwater user, accounting for >70% of human water withdrawals (Siebert and Döll 2010). To quantitatively underpin water targets in the SDG framework (6.4, specified below) that bridge sustainable food production, ecosystem maintenance, and water scarcity issues, we here quantify the degree to which present irrigated agriculture contributes to a transgression of EFRs. Using EFRs as an indicator is compatible with the regional planetary boundary for human freshwater use that accounts for the spatial and temporal pattern of local tolerance levels of water use and their transgression, as opposed to the not yet breached global boundary (Gerten et al. 2013; Steffen et al. 2015). In other words, we show how much of irrigated food production would be affected if such policy goals were implemented worldwide in the vein of propositions in the Brisbane Declaration (Brisbane Declaration 2007) and other aquatic ecosystem policy recommendations (European Comission 2015; Le Quesne et al. 2010). In turn, we assess if more effective farm water management can outweigh associated production "losses" without compromising the aquatic ecosystems.

To approach such analyses at global scale we employ an advanced dynamic global biosphere model that represents natural and agricultural vegetation with associated ecological, hydrological and biogeochemical processes — including river flows, here newly implemented EFR regulations, irrigation, and crop production — in a single internally consistent framework at high spatio-temporal resolution (Jägermeyr et al. 2016). The EFRs are defined here as the daily river flow needed to maintain river and delta ecosystem services and, thus, the human livelihoods that rely upon them (Brisbane Declaration 2007). Reflecting methodological uncertainty and varied policies concerning the fraction of river flow which should remain untouched, we apply three differing methods to allocate flow volumes to EFRs (Tessmann 1980; Smakhtin et al. 2004; Pastor et al. 2014). Simulations are performed for the time period 1980–2009, with and without consideration of EFRs. In the former case, water withdrawal for irrigation and other purposes (household, industry and livestock, HIL) is disallowed as long as it would tap EFRs. To put irrigation into perspective of total food production, we also illustrate a scenario in the absence of irrigation and highlight an exemplary scenario of moderate irrigation system upgrades (see Methods in the Appendix B.2.3 for details).

Table 4.1.: Agricultural impacts under different irrigation and flow conservation scenarios. Change in global kcal production and the proportion of affected area[1] in the total absence of irrigation[2] (**1.**), with irrigation constrained by environmental flow requirements (EFRs) (**2.**), and with upgraded irrigation[3] constrained by EFRs (**3.**) — all compared to the current situation (1980–2009). Also shown are associated changes in irrigation water withdrawal (IWD) and consumption (IWC)[4]. Values for 2. and 3. refer to the mean of three EFR methods (with standard deviation in parentheses)[5].

Scenario	Total kcal [% *change*]	Irrigated kcal [% *change*]	Total area affected[1] [%]	Irrigated area affected[1] [%]	IWD [% *change*]	IWC [% *change*]
1. No irrigation	-14.7	-44.4	32.5	81.3	-100.0	-100.0
2. Respect EFR	-4.6 (±0.8)	-13.9 (±2.5)	16.1 (±1.8)	52.2 (±3.9)	-41.4 (±5.8)	-35.1 (±5.6)
3. Respect EFR with irrigation upgrade[2]	-0.1 (±1.0)	5.6 (±2.9)	12.0 (±2.4)	33.6 (±7.4)	-54.4 (±4.3)	-34.8 (±5.2)

[1] Kcal loss $\geq$ 10%, [2] Irrigated cropland yet sustained by precipitation, [3] Surface irrigation replaced by sprinkler systems (except paddy rice) and half of saved consumptive water used to expand irrigation into neighboring rainfed cropland (see Methods), [4] Kcal production and area affected refer to cropland area, while IWD and IWC refer to the total irrigated area (incl. cash crops, cotton, etc.), [5] Compare Table B.1 for absolute values and respective EFR simulations.

4.3. Results

Our results show that today's human water withdrawals, 2409 km^3 for irrigation and 1071 km^3 for HIL, harm many river stretches around the world. Figure 4.1 lays out regions and the degree to which EFRs are currently undermined to sustain the human water demand. EFR breaches reach a level beyond the uncertainty range (given by the three estimation methods applied, see Figure B.1), and thus indicate severe degradation, especially in West, Central, and South Asia, the Mediterranean region, North America, and in the North China plain. Figure 4.1 highlights severe hydrologic alterations at selected river locations, together with a global map illustrating the proportion of mean annual EFR deficits (EFR minus discharge, if > 0) and current mean annual discharge. The Indus river in Pakistan unfolds a dramatic case, where this ratio exceeds 100% at annual level — i.e. EFRs amount to twice the remaining current discharge — while they remain unmet throughout 11 months per year (Figure 4.1). Yet, we also find alarming EFR breaches along many other rivers such as the Amu Darya, Euphrates, Yellow, Ganges, Murray, and Rio Grande. Figure B.2 shows EFR transgressions in terms of the total annual deficit and the number of months with transgressions. 31% of global EFR deficits occur in Pakistan alone, reaching 58.4% together with India (17.7%) and China (9.7%). Global EFR deficits involve a water overuse of 948 km^3/yr

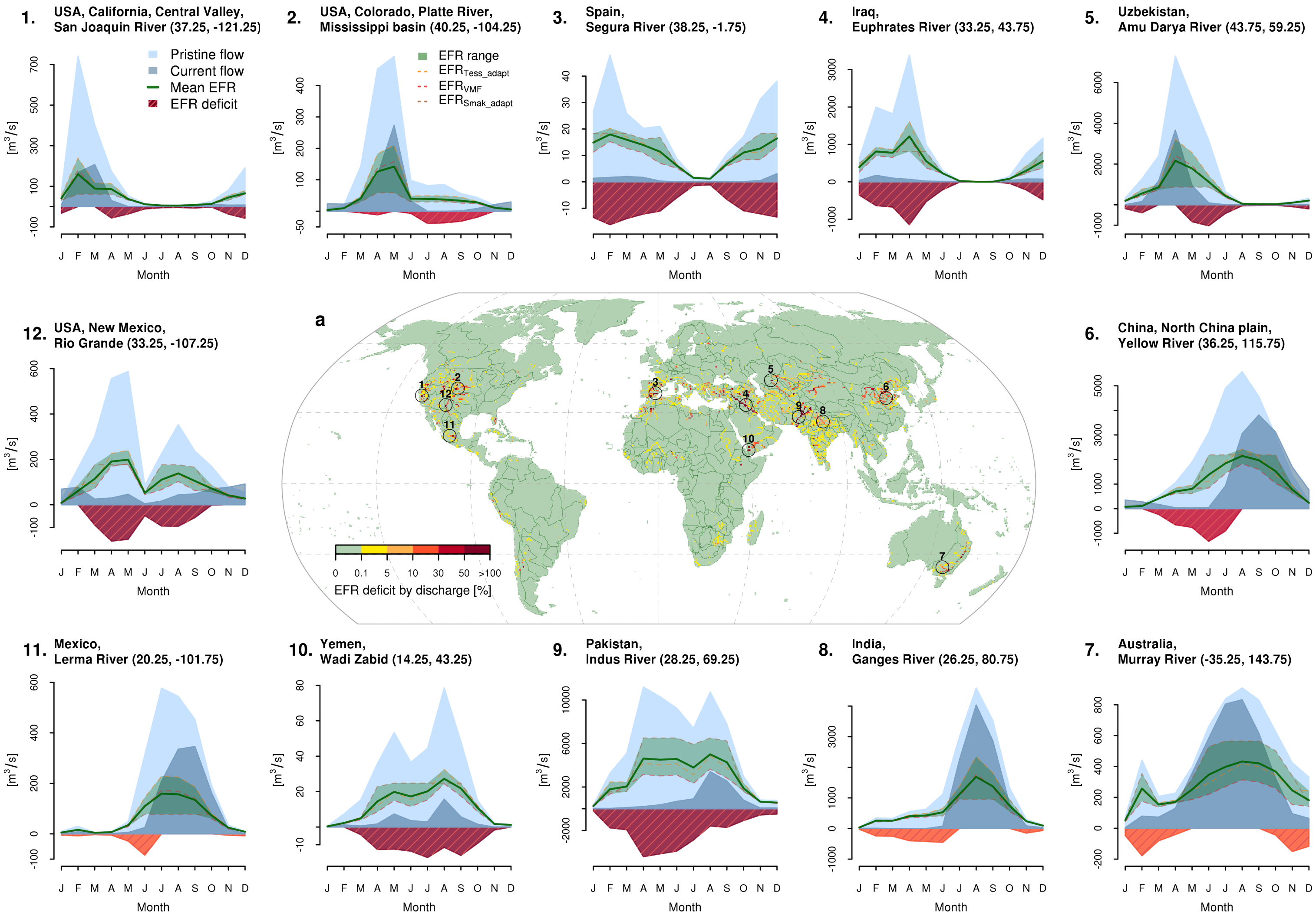

Figure 4.1.: Severe hydrologic alterations at selected river stretches. Hydrographs **1.–12.** depict seasonal flow alterations (pristine versus current discharge) together with EFR estimates and the resulting EFR deficit (EFR minus current discharge, if > 0). Different EFR methods (mean, Tessmann (1980), VMF (Pastor et al. 2014), Smakhtin et al. (2004), see Appendix B.2.1) are indicated through different line types, EFR deficit relates to the mean of EFR methods (1980–2009). Case study locations (latitude, longitude coordinates in figure title) are superimposed on the map (**a**), which additionally illustrates the proportion of mean annual EFR deficits and mean annual discharge (1980–2009, 0.5° resolution).

for irrigation (equalling 39% of total current irrigation water use) and a further 226 km^3/yr (22%) for HIL (Table 4.1 and B.1; if not indicated otherwise results refer to the mean of three EFR methods).

Current food production thus heavily relies on water that would actually be needed to sustain riverine ecosystems. If environmental policies to respect EFRs came into practice — also in regions where irrigated food production currently depends on such — 51% of global irrigated cropland would face kcal production losses $\geq$10% (see our further simulations, Table 4.1). Amongst intensely irrigated regions, like many Mediterranean countries, North America, and particularly in parts of West, Central, and South Asia, losses would reach >20% at the aggregated level of Food Production Units (FPUs, Figure 4.2b).

Total global kcal production would be subjected to a 4.6% decline, corresponding to a 13.9% loss of irrigated production (Table 4.1). Note that while kcal production on irrigated land makes up $\sim$33% of total production (confirming earlier estimates (Siebert and Döll 2010)), irrigation water contributes 15% to overall global kcal production, while the remainder is sustained by precipitation (Table 4.1). In specific regions, however, the relative contribution of irrigation is much higher, as illustrated in Figure 4.2a. Figure 4.3 shows country-level aggregations of EFR constraints on total and irrigated kcal production.

Regions that are simulated to undergo a $\geq$10% production decline with rigorous implementation of EFRs are currently inhabited by 1.1 billion people, 80% in developing countries. Since agriculture is at the center of development and poverty reduction, unambiguous societal impacts are to be expected in default of other adaptation or compensation measures. Case study observations confirm complex difficulties in water re-allocation and infrastructure re-organization for ecosystem conservancy if environmental flows are tapped already (Le Quesne et al. 2010; Blanco-Gutierrez et al. 2013; Hermoso et al. 2012). It is yet a prerequisite to avoid additional and sometimes irreversible degradation of aquatic ecosystems and linked therewith to achieve stable and resilient food production systems, needed to ground nested environmental, social, and economic sustainability.

Field-based and global modelling studies indicate that management improvements can advance crop water productivity on a considerable scale (Deng et al. 2006; Molden 2007; Brauman et al. 2013; Liu et al. 2013). To be paired with EFR constraints, we here develop an irrigation upgrade scenario as one example out of a spectrum of effective farm water management options (Jägermeyr et al. 2016).

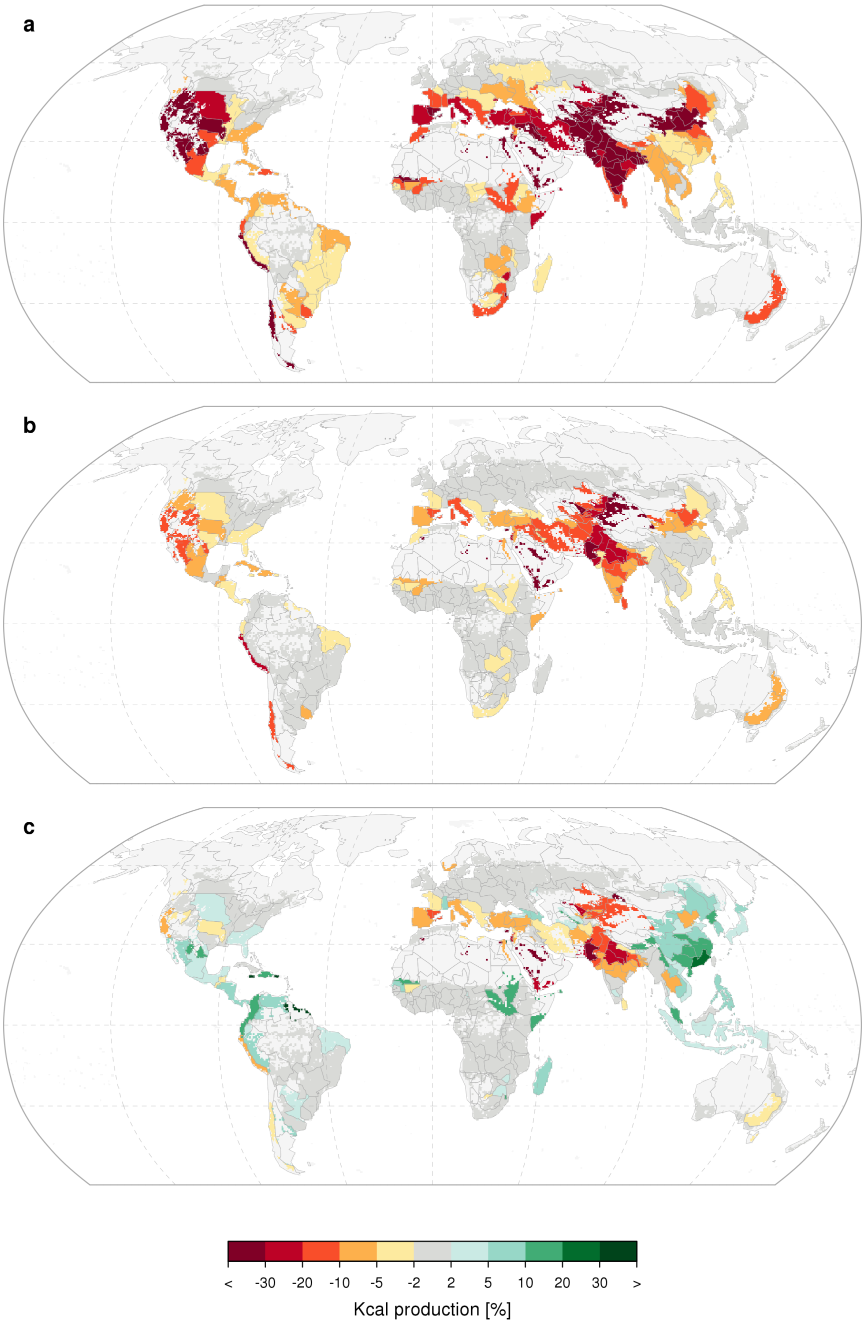

Figure 4.2.: Governing environmental flows affects food production. The maps illustrate the change in total (i.e. rainfed and irrigated) kcal production in the absence of irrigation (**a**), with irrigation constrained by EFRs (mean of three EFR methods) (**b**), and with upgraded irrigation (see Table 4.1 and Appendix B.2.3) constrained by EFRs (**c**), with respect to the current situation and aggregated to Food Production Units (1980–2009). Regions with marginal change are shaded (dark grey) and cells without significant cropland fraction (<0.1%) are masked (light grey).

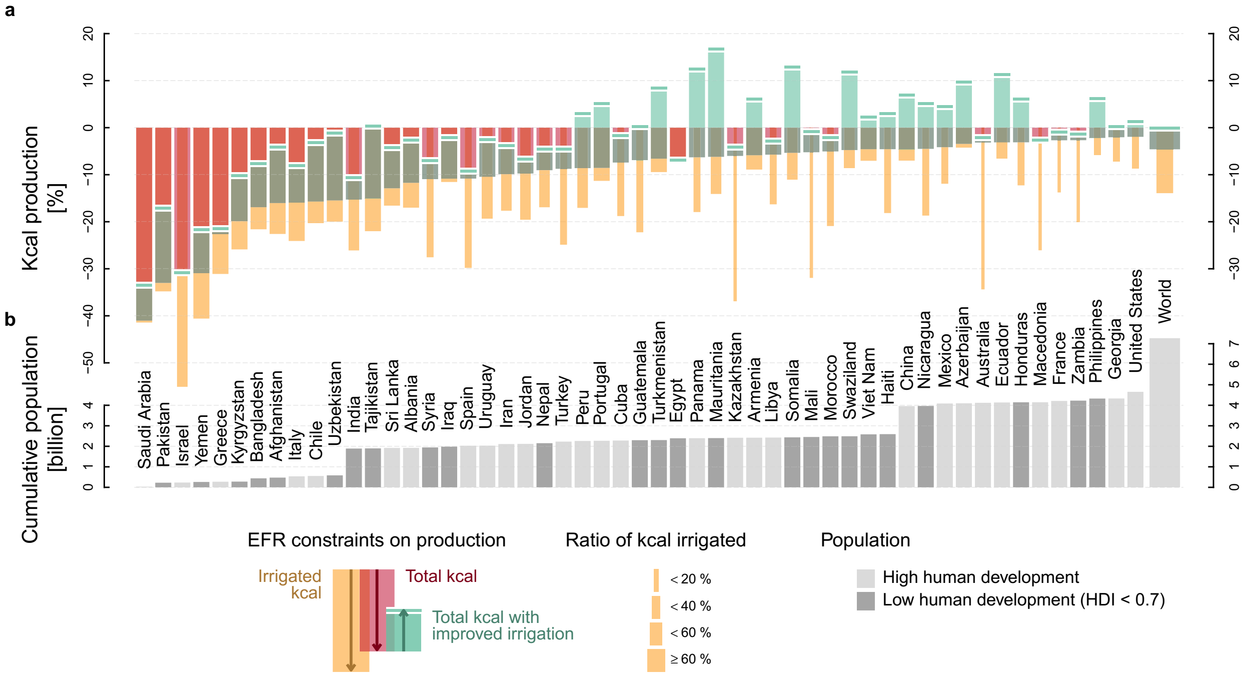

Figure 4.3.: EFR constraints on country-level kcal production under current and improved irrigation. Countries are ordered by the sensitivity of total kcal production to EFR-constrained irrigation (red) (**a**). The effect on irrigated production is shown in beige, and total production with improved irrigation in mint, all shown as changes to the current situation (details in Table B.2). The cumulative population is shown in the bottom chart (**b**), separated for high and low values in Human Development Index (HDI) (UNDP 2015).

Our simulations suggest that a transition from surface to sprinkler irrigation systems (using half of thus saved consumptive losses for expansion) would suffice — at global level — to outweigh kcal losses associated with a worldwide implementation of EFR policies (Table 4.1 and Figure 4.3). Irrigation withdrawals would thereby further decrease to about half the current amount through reductions in conveyance losses and return flows. Irrigation water consumption (withdrawals minus return flows and drainage losses) remains at the same level as under EFR constraints without irrigation improvements (∼34% below current value), but with higher shares of productive water consumption (plant transpiration), which reflects the increase in irrigation water productivity (Jägermeyr et al. 2015) (Table 4.1).

Yet, even under such improved management, 35% of irrigated cropland would remain with a ≥10% kcal loss, mostly in Central and South Asia, which is compensated at global level by production gains in other regions, notably in East Asia (Table 4.1, Figure 4.2c). More ambitious interventions would be needed to minimize local impacts in regions with strong irrigation dependency and significant EFR deficits. For example, combinations of different water management strategies; rainwater management (water harvesting, mulching, conservation tillage) and large-scale irrigation upgrades are associated with sizeable potentials in these regions (Jägermeyr et al. 2016). A scenario of integrated water management, combining the irrigation upgrade scenario presented above (Table 4.1) with modest forms of rainwater management (25% of surface runoff collected for supplemental irrigation and 25% of soil evaporation alleviated, see Jägermeyr et al. (2016) for details), is simulated to compensate EFR constraints while improving global total kcal production by 9.9% compared to the current situation (Figure B.3 and B.4). Eventually, incorporating ecological landscape approaches offer additional important merits such as soil fertility optimization and advanced crop varieties that will further maximize synergies and thus crop water productivity — promising examples have been demonstrated (Pretty et al. 2006; Chen et al. 2014; Rockström et al. 2016). Overall, the here quantified water management strategy is a showcase to illustrate opportunities to thrive within planetary environmental guardrails (De Fries et al. 2012). While not exhaustive, it highlights that farm water management across scales, linked to sustainable environmental flow regulations, would greatly assist the intricate task of such implementations paired with the goals of poverty reduction and agricultural productivity increase as outlined by the SDGs.

4.4. Discussion

A number of local EFR implementations prove successful (Le Quesne et al. 2010), e.g. Uzbekistan set clear policy targets for water use and savings and was able to reduce its proportion of water resources used (Evers 2015). The 'redline' water policies in China illustrate the integration of national legislations with local institutional frameworks (Liu et al. 2013). Although the validity of setting EFRs has become internationally accepted and in many countries provisions are being developed (Brisbane Declaration 2007; Le Quesne et al. 2010; European Comission 2015), the systematic and comprehensive quantification of EFRs poses methodological, institutional, and financial challenges and is thus still insufficient. Together with often ineffective governance, this explains why existing licenses and policies are not yet being implemented (Le Quesne et al. 2010; Biermann et al. 2012), although it is clear that EFR assessment and regulation should be a basic requirement of Integrated Water Resource Management, as e.g. outlined in the EU Water Framework Directive (European Comission 2015). That said, the EFR concept still has not gained the critical

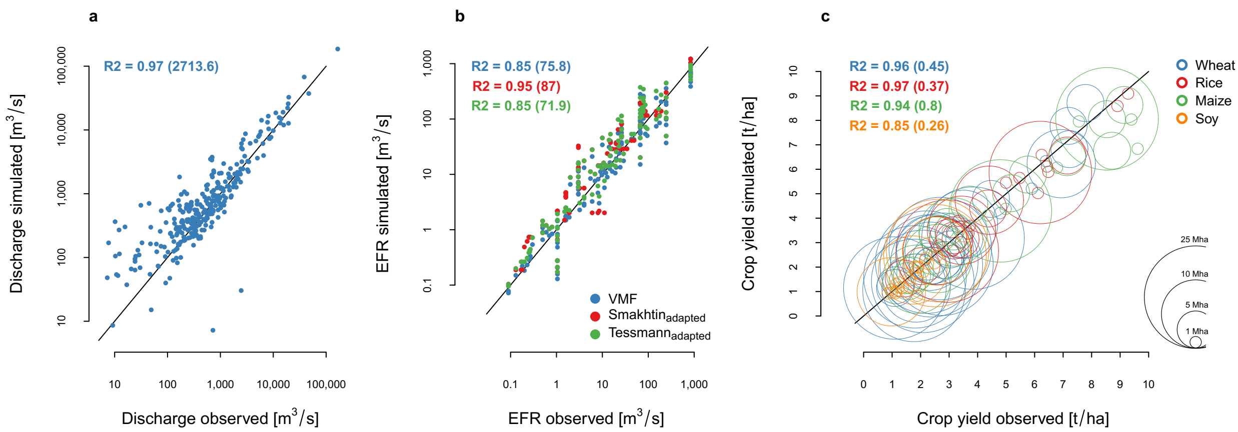

Figure 4.4.: Evaluation of LPJmL-simulated key variables. Validation results against observational data are highlighted for mean annual discharge (**a**), environmental flow requirements respectively for three differing calculation methods (**b**), and country-level crop yields (calibrated for management intensity) for main staple crops and the respective top 30 producer countries, chart symbols are scaled by country cropland extent (**c**). The coefficient of determination (R^2) is shown along with the root mean square error in parenthesis (all data 1980–2009, further details in Appendix B.2.4).

influence needed to ensure environmentally sustainable basin management in competition with other water users like agriculture and industry (Poff et al. 2010).

To develop effective national policy mechanisms, comprehensive local and regional assessment and monitoring programmes comprising field data, regional models, and expert judgement are inevitable (Poff et al. 2010; Acreman and Ferguson 2010; Le Quesne et al. 2010). However, we also acknowledge the need for more cost-effective, flexible EFR quantifications that, most importantly, conflate the global picture and provide assistance in international decision making, as particularly needed in the process of implementing the ambitious but unspecified SDG water agenda. Through methodological simplifications (e.g. channel and habitat maintenance floods not considered) with a consistent approach at global level, this study adds quantitative evidence toward that end, providing a process-based quantification of EFRs in dynamic coupling with crop production, while accounting for seasonal variability and high spatial detail. The well-validated calculation approach (Figure 4.4) appears robust as we incorporate three different EFR methods and the dynamic modelling capacity plays out water trade-offs along the river network. Moreover, we assess the current pressure on the freshwater boundary needed to be overcome in a sustainable farming system. Our study is thus in support of the 2030 Agenda for Sustainable Development (United Nations 2015a).

The implementation of the SDG agenda clearly requires operative and dedicated governance, but the current lack of established tools and thresholds to quantify related targets form a barrier to translate the agreed principles into concrete action. For example, the indicator for sustainable freshwater withdrawals (6.4.2) was proposed to be directly linked to the EFR concept (ECOSOC 2016b), but ultimately not stipulated. We here argue that accounting for EFRs is pivotal for attaining sustainable withdrawals (target 6.4) and food production systems (target 2.4), and that the EFR concept may form a basis on which to build operative policy measures, thereby linking the planetary boundaries with the 2030 Agenda. The planetary boundary for human freshwater use defined on behalf of the EFR concept provides a clear and actionable target, but further dimensions also need to be addressed (inaccessible flows, groundwater, pollution).

Finally, our study highlights that operationalizing freshwater sustainability in face of internationally stipulated goals for food security and poverty reduction would greatly benefit from integrated strategies that put strong emphasis on adaptation measures through improved farm water management. However, associated opportunities in e.g. rainwater harvesting have not gained required international attention among high-level development policies (Rockström and Falkenmark 2015). Advances in sustainable intensification are coupled to important socio-economic and environmental co-benefits (Rockström et al. 2016), which become particularly relevant in view of agricultural outlooks suggesting that crop calorie production needs to be increased by >60% in the forthcoming decades to eradicate hunger among the growing human population (FAO 2016). How to achieve this goal against a backdrop of climate change and environmental degradation, while staying within the safe operating space of the Earth system as delineated by the nine planetary boundaries remains one of the grand challenges for human ingenuity.

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Contributions J.J. and D.G. designed the study. J.J. developed the model code with contributions from A.P. J.J. performed the model simulations and analysis and wrote the paper with substantial contributions from D.G. and further contributions from H.B. and A.P..

Chapter 5.

Integrated crop water management might sustainably halve the global food gap

An edited version of this chapter, supplemented by Appendix C, has been published in the journal *Environmental Research Letters*[1]:

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[1]Featured in the special issue *Focus on Food, Trade and the Environment*, edited by David Seekell, Paolo D'Odorico, and Graham MacDonald.

5.1. Abstract

As planetary boundaries are rapidly being approached, humanity has little room for additional expansion and conventional intensification of agriculture, while a growing world population further spreads the food gap. Ample evidence exists that improved on-farm water management can close water-related yield gaps to a considerable degree, but its global significance remains unclear. In this modeling study we investigate systematically to what extent integrated crop water management might contribute to closing the global food gap, constrained by the assumption that pressure on water resources and land does not increase. Using a process-based bio-/agrosphere model, we simulate the yield-increasing potential of elevated irrigation water productivity (including irrigation expansion with thus saved water) and optimized use of *in situ* precipitation water (alleviated soil evaporation, enhanced infiltration, water harvesting for supplemental irrigation) under current and projected future climate (from 20 climate models, with and without beneficial CO_2 effects). Results show that irrigation efficiency improvements can save substantial amounts of water in many river basins (globally 48% of non-productive water consumption in an "ambitious" scenario), and if rerouted to irrigate neighboring rainfed systems, can boost kcal production significantly (26% global increase). Low-tech solutions for small-scale farmers on water-limited croplands show the potential to increase rainfed yields to a similar extent. In combination, the ambitious yet achievable integrated water management strategies explored in this study could increase global production by 41% and close the water-related yield gap by 62%. Unabated climate change will have adverse effects on crop yields in many regions, but improvements in water management as analyzed here can buffer such effects to a significant degree.

5.2. Introduction

Demand for food increases as populations grow and gain wealth, thus the world might need a 60–100% extra kcal production by 2050 to end hunger (IAASTD 2009; Tilman et al. 2011; Alexandratos and Bruinsma 2012; Valin et al. 2014). However, it is becoming increasingly apparent that planetary guardrails narrow down humanity's prospects for additional appropriation of resources and conventional intensification of agriculture (Steffen et al. 2015). Inevitably, competition for energy, land and water rises with growing food demand, which fuels the challenge of closing the global food gap (crop calorie requirements above domestic production and imports, now and in the future) (e.g. Godfray et al. 2010; Foley et al. 2011; Searchinger et al. 2013). Climate change might exacerbate this situation by increasing water stress and hydro-climatic variability particularly in developing countries (Porter et al. 2014; Rosenzweig et al. 2014).

Agriculture is the single largest user of freshwater and the most important reason why the world is transgressing planetary boundaries (Rockström and Karlberg 2010). The challenge of producing enough food becomes especially delicate, as it must be met mainly on currently cultivated land since expansion and conventional intensification of agriculture comes at major environmental costs (local to global scale factors: erosion, biodiversity loss, salinization, water pollution and eutrophication, water scarcity, greenhouse gas emissions) (Matson 1997; Foley et al. 2005; Reynolds et al. 2015). Furthermore, significant yield gaps exist across various farming systems, indicating a substantial scope for yield gains through mitigation of nutrient and water deficiencies (Mueller et al. 2012; Licker et al. 2010; *Global Yield Gap Atlas* 2015).

Increasing production on existing agricultural land by managing available resources more efficiently, placing less pressure on the environment and sustaining future capacities, i.e. sustainable intensification, is thus seen as an important part of a solution and high on the global policy agenda (Tilman 1999; The Royal Society 2009; Garnett et al. 2013; World Bank 2013; Dobermann and Nelson 2015). The renewed Sustainable Development Goals now stipulate sustainable agriculture as an agreed goal among all nations (United Nations 2015b), but there is little quantitative evidence of how to achieve it. While most global strategies focus on improving soil fertility, Rockström and Falkenmark (2015) urge an international high-level consideration of integrated crop water management. In fact, such water productivity improvements (i.e. increasing the yield output per unit of water consumed) in both rainfed and irrigated systems paired with an increase in consumptive water use are a *sine qua non* for raising food production to the tremendous amount required (Molden 2007; IAASTD 2009).

However, the attainable extent and potential of integrated crop water management at the global level under both current and future climates remains insufficiently quantified (e.g. Pretty et al. 2011; Rost et al. 2009; IAASTD 2009; Brauman et al. 2013). In this global modeling study we investigate the potential to increase yields through large-scale implementations of integrated crop water management (defined here as a mix of various farm water management interventions).

Particularly in semi-arid rainfed agriculture, subject to the largest water constraints to low yields, rainfall variability (dry spells, periodic water scarcity) often poses a much greater problem than the total amount of precipitation. In addition, in semiarid tropical systems root zone drought and low yields (1–2 tha^{-1}) are often caused by poor farm water management with excessive on-farm

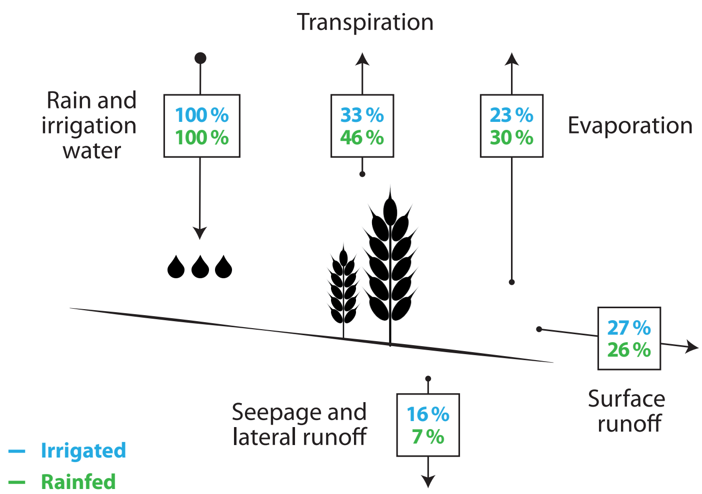

Figure 5.1.: Hydro-climatic opportunities in crop water management. Rainfall and irrigation water partitioning as growing season averages across global cropland, calculated with LPJmL (1980–2009). Blue numbers refer to irrigated systems (precipitation plus irrigation withdrawal), green numbers refer to rainfed systems. Evaporation also includes interception losses. Note that water outflux can exceed growing season rainfall due to soil moisture availability at planting. Productive consumption (i.e. transpiration) can be much lower regionally; generalized estimates for rainfed systems in sub-Saharan Africa are: transpiration 15–30%, evaporation: 30–50%, runoff: 10–25%, seepage: 10–30% (Rockström and Falkenmark 2015). Spatial patterns in transpiration coefficient simulated with LPJmL are displayed in Figure C.1.

water losses (Oweis and Hachum 2006; Rockstrom et al. 2007; Wani et al. 2009). Accordingly, the transpiration coefficient (TC, crop transpiration per unit rain and withdrawn irrigation water, Figure 5.1) is often <30%, as non-productive soil evaporation can consume up to 50% on low-yielding fields (Daamen et al. 1995; Rockström 2003; Wani et al. 2009), and 10–30% can be lost to surface runoff (Welderufael et al. 2008; Araya and Stroosnijder 2010).

These factors indicate key hydro-climatic opportunities. In fact, there is a portfolio of measures available to increase plant water availability through e.g. maximizing soil infiltration, minimizing soil evaporation, collecting surface runoff for supplemental irrigation, and improving irrigation systems (to expand irrigated areas using saved water). Supplemental irrigation during dry spells can trigger important positive production shifts (Fox and Rockström 2003; Biazin et al. 2012; Burney et al. 2013), and water harvesting (WH) and soil moisture conservation (SMC) techniques can double smallholder yields in drought-prone regions while at the same time improving resilience to climate risks (Rockström et al. 2003; Oweis and Hachum 2006; Dile et al. 2013). These long-known practices are being implemented sporadically around the world, leaving open vast potential to scale up (Barron et al. 2015; Searchinger et al. 2013; Mati et al. 2007). Irrigated farming systems on the other hand, are the single largest global user of water abstractions (80–90% of consumption), but they use water often inefficiently (Gleick et al. 2009; Molden 2007). Irrigation improvements have the potential to save and redistribute water to underperforming systems (Rockstrom et al. 2007; Kijne et al. 2009; Brauman et al. 2013; Jägermeyr et al. 2015; Fishman et al. 2015). In particular the combination of such measures, i.e. integrated farm water management proved successful to boost yields across various farming systems (Oweis and Hachum 2003; Molden 2007; Mazvimavi et al. 2008).

However, the potential significance of integrated crop water management at the global level remains unclear, because upscaling is a challenge given the heterogeneity of farming systems and downstream water trade-offs (e.g. Falkenmark et al. 2001; Ngigi 2003; Pretty et al. 2011; Dile et al. 2013). Only few studies have used the capacity of modeling approaches in evaluating complex interactions of up-scaling water management interventions (e.g. Tsubo and Walker 2007; Kahinda et al. 2007; Wisser et al. 2010; Barron et al. 2015). Lebel et al. (2015) quantify WH potential for maize in the whole of Africa using an empirical approach. Rost et al. (2009) simulate effects of WH and SMC on global crop NPP with the dynamic agro-hydrological model used herein. A knowledge gap remains, to provide a global assessment of integrated water management in rainfed and irrigated agriculture and using a large ensemble of climate change scenarios.

This study investigates systematically the global potential of integrated crop water management through implementing the most approved interventions into the dynamic global bio-agrosphere model, LPJmL. We present a process-based simulation of crop yields with high spatial, temporal and agronomic detail, explicitly accounting for downstream effects and catchment hydrology. The study shows by how much (i) global crop production could be intensified sustainably (in terms of not using additional water or land inputs), (ii) the water gap (see Figure 5.2) could be closed, and (iii) these opportunities might buffer potential climate change impacts, assuming various ambition levels for large-scale adoption of integrated crop water management.

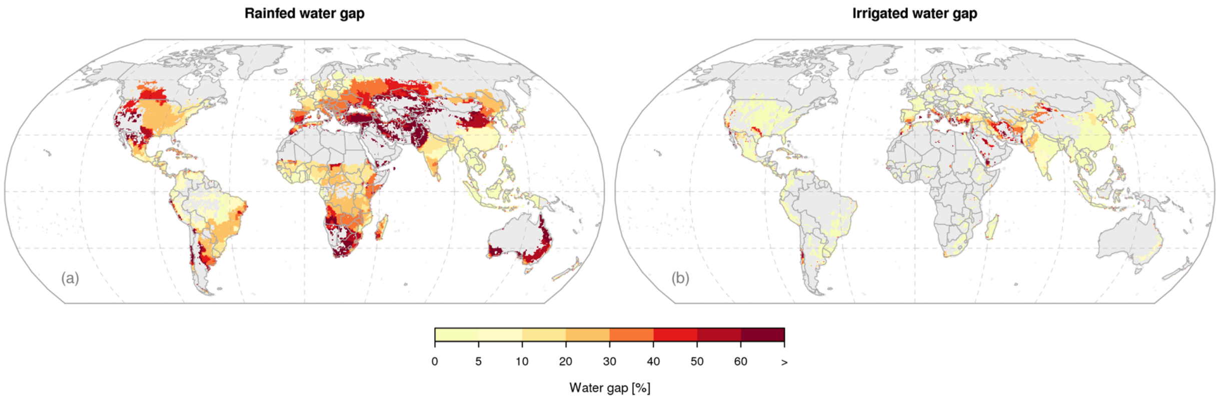

Figure 5.2.: Global distribution of the water gap. "Water gap" (i.e. the gap between current and potential yields in the absence of water constraints) at basin level simulated by LPJmL for rainfed (**a**) and irrigated agriculture (**b**), averaged for the time period 1980 to 2009. Global area-weighted averages are 29% for rainfed and 6% for irrigated systems.

5.3. Methods

The representation of water harvesting, soil moisture conservation and irrigation transitions in LPJmL is outlined first (summarized in Table 5.1), followed by basic characteristics of the model and the simulation setup.

5.3.1. Simulation of water management interventions

Ex situ water harvesting (WH_{ex})

This measure describes the concentration, collection, and storage of surface runoff in ponds or cisterns for supplementary irrigation (SI) during dry spells. Reservoirs are often sized to provide about 100–200 mm SI (Biazin et al. 2012; Barron and Okwach 2005; Oweis and Hachum 2006). Its implementation is site-specific, depending on various biophysical, economic and social factors (Barron et al. 2015; Studer and Linger 2013). We therefore simulate in LPJmL four ambition levels for harvesting runoff during the growing season: on 10, 25, 50, and 85% of rainfed cropland in each grid cell with a maximum storage capacity of 200 mm, respectively. Case studies support similar up-scaling potentials across watersheds using gravity-fed and pump-based SI (Kahinda et al. 2008; Barron et al. 2015). We define a rather high storage capacity to allow evaluating SI potentials, despite challenges to its large-scale implementation (in section 3.6. we show that 100 mm suffice in

Table 5.1.: Portfolio of water (and soil) management interventions simulated in this study.

Name	Goal	Measure	LPJmL implementation	Rainfed / irrigated
Soil moisture conservation (SMC)	Alleviation of non-productive soil moisture depletion	Mulching (organic residues, plastic films), conservation tillage	Soil evaporation during growing season reduced by 10–85%	Rainfed and irrigated cropland
***ex situ* water harvesting (WH$_{ex}$)**	Supplementary irrigation for dry spell mitigation	Collecting surface runoff in designated catchment area, storage in cisterns etc., supplementary irrigation	Surface runoff during growing season collected on 10–85% of cropland (storage capacity 200 mm), suppl. irrigation if soil moisture <40% of field capacity	Rainfed cropland
***in situ* water harvesting (WH$_{in}$)**	Maximizing soil infiltration capacity and reducing non-productive surface runoff	Pitting, contouring, terracing, micro-basins, plowing, crop residues, conservation tillage	Increased infiltration rate (see EQ 1)	Rainfed cropland
Irrigation improvement (IRR)	Reducing non-productive water consumption and using thus saved water for expansion	Improving performance of irrigation systems	Replacing surface irrigation with sprinkler or drip systems	Irrigated cropland, expanding into rainfed with saved water

95% of all cases). Water is assumed to be reapplied on the same land where it was collected, if (i) root available relative soil moisture <40% of field capacity, (ii) daily precipitation is below 5 mm, and (iii) soil water supply falls short of soil water demand. Sensitivity analyses for the cistern size and irrigation threshold are displayed in Figure C.2.

In situ water harvesting (WH$_{\mathrm{in}}$)

Micro-catchment systems, e.g. pitting, terracing, micro-basins, but also conservation tillage, and mulching can hinder water from running off the field and thus help increasing infiltration capacity. Particularly the combination of micro-catchments and mulching is observed to reduce runoff and soil evaporation considerably (Botha et al. 2007; Biazin et al. 2012). In LPJmL, infiltration rate In depends on soil properties, current soil moisture and the infiltration parameter p. By default, without management interventions, $p = 2$, but here we also simulate increased infiltration rates assuming four different intensity levels ($p = 3, 4, 5, 6$).

In is calculated for the upper soil layer as:

$$In = prir \times \sqrt[p]{1 - \frac{w_a}{W_{sat} - W_{pwp}}}, \quad (5.1)$$

where $prir$ is daily rain and applied irrigation water, w_a is the available soil water content, and W_{sat} and W_{pwp} are soil water content at saturation and wilting point, respectively (all in mm). A sensitivity analysis for p is displayed in Figure C.2. Hereinafter, WH refers to the combination of WH_{in} and WH_{ex} measures at the four respective ambition levels.

Soil moisture conservation (SMC)

Non-productive soil moisture depletion can be alleviated through organic or plastic film mulching, and different conservation tillage systems. These techniques can improve grain yield remarkably through conserving soil moisture for additional plant transpiration, suppressing weeds, and improving cold tolerance (Liu et al. 2014). Organic crop residues covering 50% of the soil surface can reduce soil evaporation by ∼25%, plastic mulching can reduce soil evaporation by ∼50–90% (Bos et al. 2009; Bu et al. 2013). In our simulations, we reduce soil evaporation on rainfed and irrigated cropland during the growing season by 10, 25, 50, and 85%, respectively (applied as a simple factor to the evaporation calculation). SMC is also applied on irrigated fields and therefore helps saving irrigation requirements. As it is not affecting downstream water availability, SMC can be considered a "crop per drop" improvement also at basin scale.

Irrigation improvements and expansion with saved water (IRR_{exp})

Irrigation is represented through mechanistic simulation of surface, sprinkler and drip systems, depending on country and crop type. System efficiencies are directly linked to vegetation dynamics, weather and soil conditions, and water availability (Jägermeyr et al. 2015). To simulate irrigation improvements, we define three theoretical transition scenarios:

1. **"50% surface"**, half of non-paddy surface irrigation is replaced by more efficient sprinkler systems.
2. **"Best practice"**, drip systems are established where applicable (based on crop suitability, (Jägermeyr et al. 2015)), the remainder is under sprinkler irrigation, but paddy rice remains with surface systems.

3. **“All drip”**, drip irrigation on all irrigated land.

Improving irrigation performances can release water which in turn can be exploited for expanding the target area. To calculate expansion potentials, we only consider saved water that otherwise would have been consumed non-beneficially, as irrigation return-flows are often crucial for downstream water availability. Expansion of irrigated land is assumed to be further constrained by current rainfed cropland within a river basin. Table 5.3 presents global numbers of expansion.

Integrated water management

In addition to individual simulations of water management interventions, as detailed above, we run cross-combinations of WH, SMC, and IRR_{exp} (see Table 5.2), from which we select three pointer scenarios for further investigation and for climate change simulations:

Table 5.2.: Overview of model simulations. RCP = representative concentration pathways, GCMs = global climate models.

Reanalysis climate 1901–2009		Simulations
ACT	Current management calibrated with FAO data, reference run for all other simulations	1
POT	Potentially achievable yields under unconstrained water availability (nutrient deficiencies remain)	1
SMC	Soil evaporation reduced by 10, 25, 50, and 85%.	4
WH_{ex}	Surface runoff collected by 10, 25, 50, and 85%	4
WH_{in}	Infiltration rate increased in four sequential steps (EQ 5.1)	4
WH	*ex situ* and *in situ* WH combined	4
IRR	Irrigation improvements: “50% surface”, “Best practice”, “All drip”	3
IRR_{exp}	Irrigation expansion using saved consumptive water from IRR	3
IRR_{exp}+SMC_{exp}	Irrigation expansion using saved consumptive water from IRR and SMC implementation	3
Combined	Cross-combinations of SMC, WH and IRR	12
$Combined_{exp}$	Cross-combinations of SMC, WH and IRR_{exp}+SMC_{exp} (include the **“low”**,**“ambitious”**,**“max”** scenario)	12
Climate change 2009–2099: 4 RCP scenarios, 20 GCMs each, constant and transient CO_2 each		
CC	Climate change impact	160
CC + manage	CC plus water management scenarios: “low”, “ambitious”, “max”	480
	Σ	688

1. **"Low":** "50% surface" irrigation scenario + 25% SMC + 25% WH + irrigation expansion with saved water.
2. **"Ambitious":** "best practice" irrigation scenario + 50% SMC + 50% WH + irrigation expansion with saved water.
3. **"Max":** "all drip" irrigation scenario + 85% SMC + 85% WH + irrigation expansion with saved water.

It is worth to highlight that both the "max", and "all drip" scenarios are designed to evaluate planetary biophysical limits, not to represent feasible transition targets.

5.3.2. LPJmL model

The model LPJmL globally represents biogeochemical land surface processes of vegetation and soils (Bondeau et al. 2007; Fader et al. 2010; Jägermeyr et al. 2015), simulating daily water and carbon fluxes in direct coupling with the establishment, growth, and productivity of major natural and agricultural plant types at 0.5° resolution.

Agricultural land is represented by 12 specified crop functional types (CFTs), a class "others" that includes a suite of crops collectively parameterized as annual crops, and pastures (Bondeau et al. 2007). All CFTs are either irrigated or rainfed and its spatial distribution and their irrigated fraction is prescribed as in Jägermeyr et al. (2015).

Assimilated carbon (in the process of photosynthesis) is allocated to harvestable storage organs (e.g. cereal grain) and three other pools (roots, leafs, stems). Sowing dates are dynamically calculated based on climate and crop type (Waha et al. 2012). Crops are harvested when they reach maturity, defined either through a CFT-specific maximum value of daily accumulated phenological heat units or expiration of the growing season. Storage organs are subsequently removed from the field. Root growth and distribution within soil layers is CFT-specific, while the soil profile is discretized into 5 hydrologically active layers (Schaphoff et al. 2013).

Plant growth is currently not directly nutrient-limited in LPJmL, yet constrained by temperature, radiation, water and atmospheric CO_2 concentration. We calibrate crop yields with national FAO statistics based on three model parameters (as in Fader et al. 2010) to account for CFT-specific management intensities.

LPJmL partitions precipitation and applied irrigation water into interception, transpiration, soil evaporation, soil moisture, and runoff. Surplus water that cannot infiltrate generates surface runoff. Subsurface soil water above saturation runs off in lateral direction, while remaining soil water above field capacity percolates to the layer beneath, depending on its soil water content and hydraulic conductivity. Surface and subsurface runoff are accumulated along the river network and subsequently available for downstream reuse.

A recently implemented mechanistic irrigation module provides the framework for irrigation transitions (Jägermeyr et al. 2015). In addition, we account for household, industry and livestock water use and include a representation of dams and reservoirs to improve the simulation of available surface water (Biemans et al. 2011).

5.3.3. Simulation protocol

For the time period 1901–2009, we ran LPJmL forced with the Climate Research Unit's (CRU) TS 3.1 monthly climatology for temperature, cloudiness (Harris et al. 2014) and with the Global Precipitation Climatology Centre's (GPCC) precipitation data (Schneider et al. 2014). The number of monthly rain days was derived from CRU and GPCC data as described in Heinke et al. (2013). To cover uncertainties in climate change simulations (2009–2099), we considered four representative concentration pathways (RCPs: 2.6, 4.5, 6.0, 8.5), each being represented by 20 global climate models (GCMs) obtained from the CMIP5 multi-model ensemble dataset (Table C.1) (Taylor et al. 2012). Monthly GCM output was bilinearly interpolated and bias-corrected to the reference period 1970–2000 using a method adapted from Watanabe et al. (2012). To analyze the CO_2 effect on crop growth, each simulation was performed with constant (at year 2000) and transient CO_2 concentration. Model runs follow a 1000-year spinup (recycling the first 30 years of input climatology) and sowing dates are fixed during the simulation period after 1960 to allow the comparison of water management potentials between different runs and otherwise they would represent a form of adaptation not intended here.

Spatially explicit global information on cropland extent is obtained from the MIRCA2000 land-use dataset (Portmann et al. 2010). The extent of areas equipped for irrigation from 1900–2005 is imported from Siebert et al. (2015) and the distribution of irrigation systems from Jägermeyr et al. (2015). Land use patterns are fixed after the year 2005. Irrigation withdrawal is constrained by local, renewable water storage, i.e. there is no implicit assumption about contributions from fossil

Table 5.3.: Irrigation expansion potential with water savings. Global area (Mha) of rainfed and irrigated agricultural land (including pastures) aligned with irrigation water consumption (IWC, km^3) and irrigation withdrawal (IWD), for current land use and the three scenarios of combined water management "low", "ambitious", "max", including irrigation expansion (Combined$_{exp}$ in Table 5.2).

	Rainfed	Irrigated	Total	IWC	IWD
		[Mha]		[km^3]	
Actual	3984	297	4282	1268	2507
Low "50% surface" irrigation + 25% SMC + 25% WH	3895	387	4282	1350	2379
Ambitious "Best practice" irrigation + 50% SMC + 50% WH	3639	642	4282	1515	2059
Max "All drip" irrigation + 85% SMC + 85% WH	3388	894	4282	1607	1818

groundwater or diverted rivers. Only potentially achievable yields (Figure 5.2 and 5.4) are simulated under unrestricted water availability.

5.4. Results

5.4.1. Effects of integrated water management on crop production, transpiration coefficient, and the water gap

Simulated crop water management increases global kcal production by 41% under the "ambitious" scenario (all measures combined, including irrigation expansion), while using existing agricultural land, yet cutting irrigation abstractions. Production increases by more than 55% in many river basins between the Middle East, central Asia, China, Australia, southern Africa and North and South America (Figure 5.3a). Under the "low" and "max" scenario global kcal production increases by 18 and 60%, respectively (Figure 5.3b). Individual effects of irrigation transitions (IRR), soil moisture conservation (SMC) and water harvesting (WH) are specified below (Section 5.4.2 et seq.).

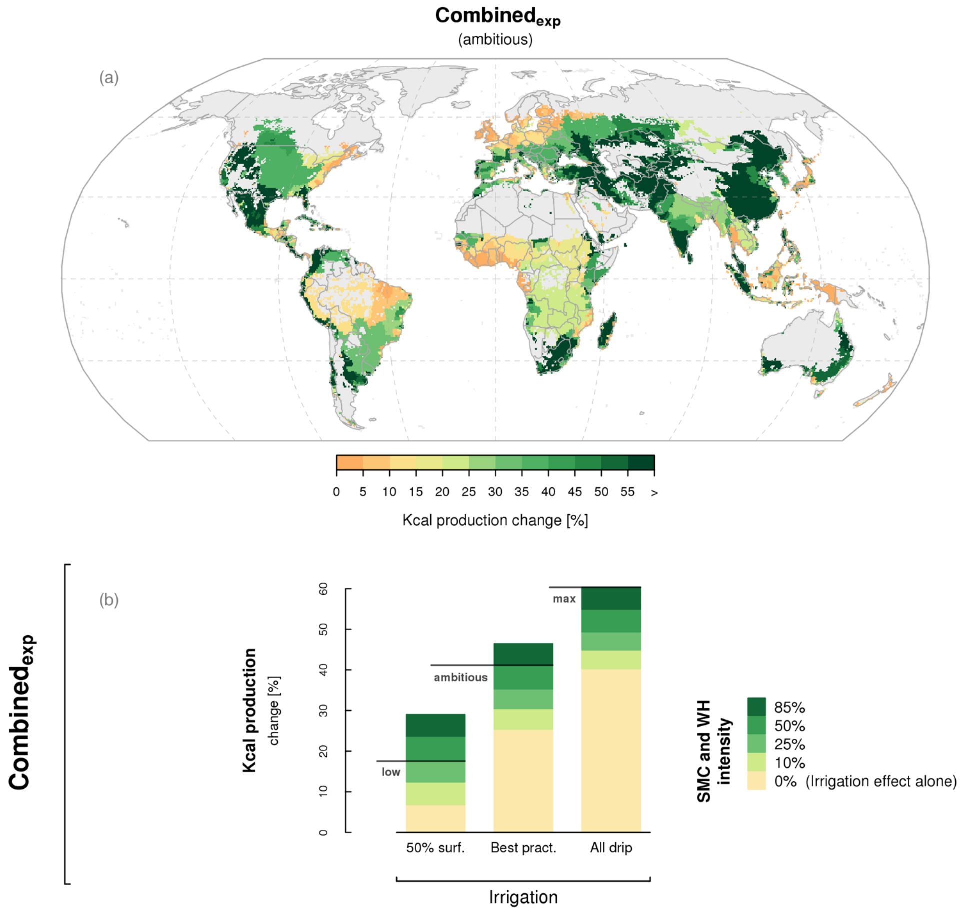

Figure 5.3.: Planetary opportunities in crop water management. Potential for increasing global kcal production through integrated crop water management (panel **a**, "ambitious" scenario). Global sums of kcal production for various simulated water management scenarios (Combined$_{exp}$, Table 5.2) is shown in (**b**), with bars representing the irrigation scenario and stacks indicating the intensity of soil moisture conservation (SMC) and water harvesting (WH). Indicated "low", "ambitious", and "max" pointer scenarios derive from the combination of each irrigation scenario with the respective SMC and WH intensity (defined in Section 5.3.1).

On current farmland, we calculate the average transpiration coefficient (TC) at 46% for rainfed and 33% for irrigated systems (Figure 5.1). Simulated water management significantly shifts water toward transpiration through alleviating soil evaporation, surface runoff and irrigation losses. Therefore, the TC (combined for rainfed and irrigated systems) increases from 42% to 49, 54, and 61%, respectively, in the "low", "ambitious", and "max" scenario.

Production gains are particularly steep in regions currently experiencing large water gaps. Figure 5.2a highlights basins where the water gap exceeds 50%, and include large parts of the Middle

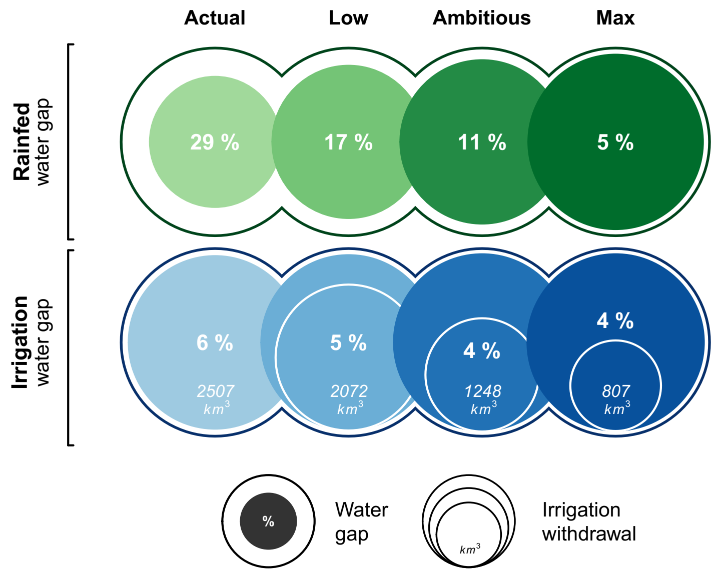

Figure 5.4.: Water management bridges the rainfed water gap and cuts irrigation water use. This illustration shows a possible closure of the water gap through crop water management in rainfed and irrigated systems. The gap is calculated as the difference between achieved production (colored circle) compared to potential production (white circle) for different management scenarios. Global irrigation withdrawal is indicated by bottom italic numbers, while the inner white ring illustrates the proportion to "actual" withdrawal. Irrigation expansion is not included. See Figure 5.2 for spatial patterns of the water gap.

East, central Asia, North China plains, Australia, southern Africa, and the western United States. Based on LPJmL, current global rainfed farming operates with a water gap of 29% relative to its unconstrained water potential (yet neglecting nutrient deficiencies). In the "low", "ambitious", and "max" scenario, this gap could be closed up to 17, 11 and 5%, respectively (Figure 5.4).

The irrigation water gap is necessarily smaller than the rainfed, as irrigation largely closes the gap. Under current conditions, global irrigated farming is simulated to be only 6% short of its unconstrained water potential (spatial patterns in Figure 5.2b). While better water management can further narrow this gap (local significance), important benefits at the global level are associated with water savings (Figure 5.4).

5.4.2. Water savings potentials of irrigation systems

Figure 5.5a confirms that improved irrigation and SMC implementations can only marginally increase irrigated production at the global level (by <2%). More importantly however, these measures ("low", "ambitious", "max" scenario without expansion) show the potential to cut consumptive losses (i.e. soil evaporation, interception, and evaporative conveyance losses) by respectively 24, 48, and 85% (Figure 5.5b). This results in significant reductions of global irrigation withdrawal from currently 2507 km^3 to 2071, 1248 and 808 km^3 (Figure 5.4), because alleviated soil evaporation and higher conveyance and application efficiencies strongly reduce irrigation requirements.

5.4.3. Irrigation expansion with saved irrigation losses

These water savings would theoretically allow for an additional 90, 345, and 597 Mha expansion into rainfed cropland, respectively, for the "low", "ambitious", and "max" scenario. These numbers are substantial in perspective of current irrigated land of about 300 Mha and the expected slow expansion pace. But future irrigation expectations are curbed due to land constraints under current system efficiencies (Alexandratos and Bruinsma 2012); farmers who pursue efforts to save water often use it to expand their irrigated share of cropland (Fishman et al. 2015).

Global total kcal production (rainfed + irrigated) could thereby increase by 7, 26, and 43% with considerably higher numbers in specific basins particularly between the middle East, large parts of Asia, and Central to North America (Figure 5.5b; aggregated to the basin level, as upstream irrigation improvements can have water trade offs downstream). Note that irrigation expansion (with higher efficiencies), but also SMC and WH, lead to higher productive plant transpiration, which increases global irrigation water consumption from currently 1268 km^3 to 1350, 1515, and 1607 km^3, respectively (Table 5.3, "low", "ambitious", "max" scenario), while non-productive losses still decrease (not all saved water used up for expansion as some basins lack sufficient available rainfed cropland, Figure 5.5a). Overall, the total global withdrawal amount is simulated to decrease by 128, 448, and 689 km^3 for the three respective scenarios, despite the growth of irrigated areas (Table 5.3).

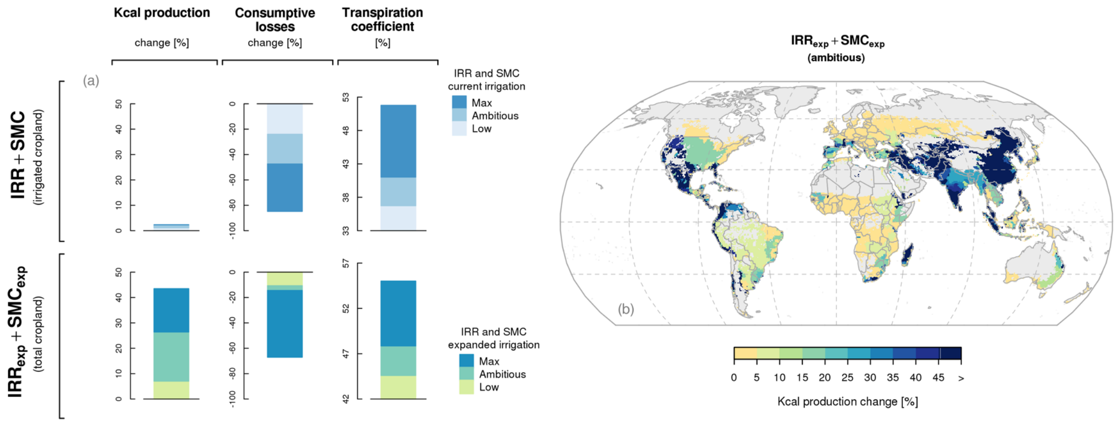

Figure 5.5.: Planetary opportunities in blue water management. Effects of irrigation improvements (IRR) and soil moisture conservation (SMC) on crop production, consumptive irrigation losses and the transpiration coefficient of irrigated cropland. Stacks in panel (**a**) show global sums for currently irrigated cropland (top row) and for total cropland with expanded irrigation into rainfed areas (bottom row, SMC does not apply to rainfed systems in this figure). The map (**b**) shows spatial patterns of changes in total kcal production with the "ambitious" IRR_{exp} + SMC_{exp} scenario ("best practice" irrigation and 50% SMC and expansion with saved water), all for the time period 1980 to 2009.

5.4.4. Effects of soil moisture conservation and water harvesting on rainfed systems

SMC shows considerable potential to amplify rainfed kcal production (3–14% globally, Figure 5.6a). Regions with high sensitivity are concentrated in semi-arid to arid regions such as the Sahel, southern Africa, central Asia, and Australia, where production increases reach >20% (Figure 5.6b, no downstream effect and thus displayed at the grid cell level). As for water harvesting, WH_{ex} exhibits much higher production potentials compared to WH_{in}, but combining both measures appears especially beneficial at low intensity levels, and could increase global kcal production by 7–24% (Figure 5.6c). Figure 5.6d shows spatial patterns of WH (50% level) with high sensitivity also in semi-arid regions, but in addition in sub-humid regions with high rainfall variability and runoff excess, across tropical and temperate regions.

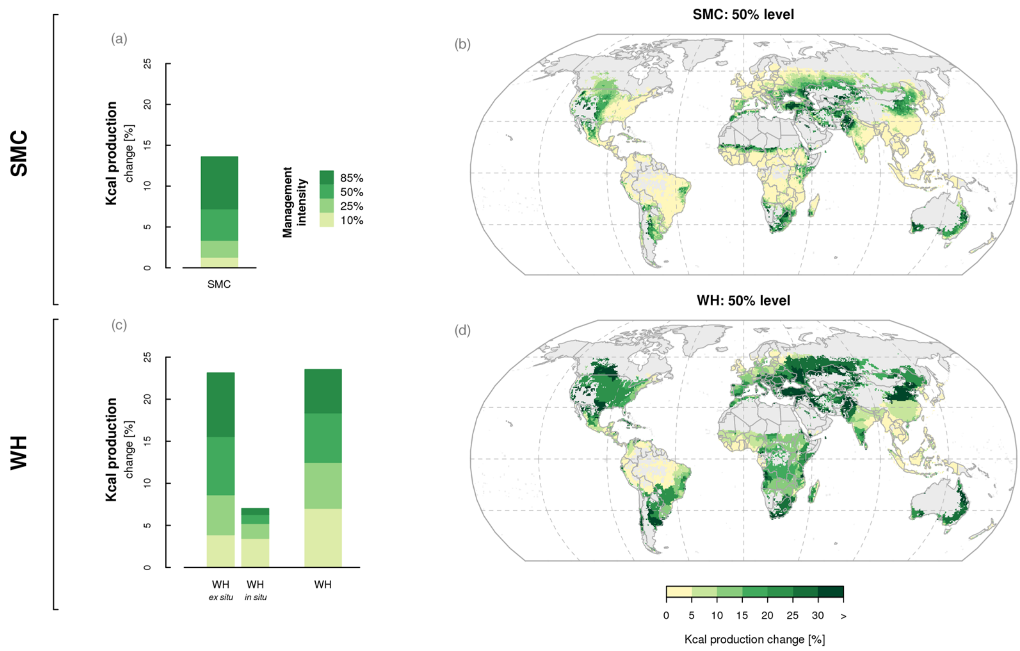

Figure 5.6.: Planetary opportunities in green water management. Effects of soil moisture conservation (SMC) and water harvesting (WH) interventions on rainfed cropping systems: barplots show global sums of kcal production change. Maps show spatial patterns of SMC (**b**) and WH (**d**), respectively at the 50% intensity level for the time period is 1980 to 2009.

5.4.5. Climate change impact

Climate change is simulated to have adverse effects on global crop production, while high uncertainty is associated with the direct effect of carbon dioxide on plant growth. In simulations with constant CO_2 concentration (performed to isolate the climate change effect), global kcal production is projected to change by -3% (RCP 2.6) to -18.2% (RCP 8.5, Table 5.4, median of 20 GCMs), mostly due to increased water deficiencies. With transient CO_2 concentration, a strong fertilization effect (in LPJmL not directly constrained by nutrient limitation) actually increases global production by 4.3% (RCP 2.6) to 13% (RCP 8.5) despite concurrent climate impacts. A "moderate" CO_2 fertilization (mean of constant and transient CO_2 simulations) suggests marginal global production changes (-2.6 to 1.6%). Regionally however, India, Pakistan, west Australia, African Sahel, and east Brazil face negative changes from -5 to <-20% under RCP 2.6 ("moderate" CO_2), while strong increases occur in large parts of Russia, east and southern Africa, and parts of central and south America (5 to >20%). In an RCP 8.5 world ("moderate" CO_2) the Mediterranean region, major

Table 5.4.: Water management buffers adverse climate change impacts. Potential climate change impact (CC) on global crop production as against three scenarios of water management under four RCP scenarios and different levels of CO_2 fertilization; for the time period 2070–2099 vs. 1980–2009, as averages across 20 GCMs.

	RCP 2.6			RCP 4.5			RCP 6			RCP 8.5		
	const.[1]	**mod.**[2]	trans.[3]	const.	**mod.**	trans.	const.	**mod.**	trans.	const.	**mod.**	trans.
CC	-3.0	**0.7**	4.3	-7.6	**0.9**	9.3	-9.4	**1.6**	12.7	-18.2	**-2.6**	13.0
CC + manage												
"Low"	12.6	**16.2**	19.8	8.1	**16.4**	24.6	5.8	**16.7**	27.5	-3.8	**11.3**	26.4
"Ambitious"	38.4	**42.2**	46.1	33.1	**41.8**	50.5	30.8	**42.2**	53.7	18.9	**34.9**	50.9
"Max"	53.1	**57.3**	61.5	47.1	**56.7**	66.2	44.6	**57.1**	69.7	31.4	**49.1**	66.8

[1]**const.**: CO_2 concentration fixed at year 2000, [2]**mod.**: moderate CO_2 effect, mean yields of constant and transient CO_2, [3]**trans.**: transient CO_2 concentration.

parts of the United States and Mexico, and southern Asia appear additionally on the map with distinct negative changes, and many basins show kcal declines from -10 to <-30% (Figure 5.7c). In the "low" scenario, most adverse climate change impacts are simulated to be buffered in a RCP 2.6 world (Figure 5.7, see Figure C.4 and C.5 for constant and transient CO_2). The "ambitious" scenario can ease negative impacts in an RCP 8.5 world in many basins, but some regions, notably east Brazil and west Africa, remain with negative impacts. Despite large uncertainties associated with the CO_2 effect, global crop production is simulated to increase by >40% under "ambitious" water management for all but the most severe climate change scenario (35% with RCP8.5, Table 5.4).

5.4.6. Evaluation of results and modeling issues

Supplemental irrigation, mulching, and conservation tillage demonstrably increased yields in case studies by 56%, 44%, and 30%, respectively (Araya and Stroosnijder 2010; Welderufael et al. 2008; Fox and Rockström 2003). A major case study (286 projects in 57 countries) documents average yield increases by 79% through a number of conservation agriculture interventions, including water harvesting and conservation tillage (Pretty et al. 2006). A wider collection of case studies shows similar ranges (Table C.2).

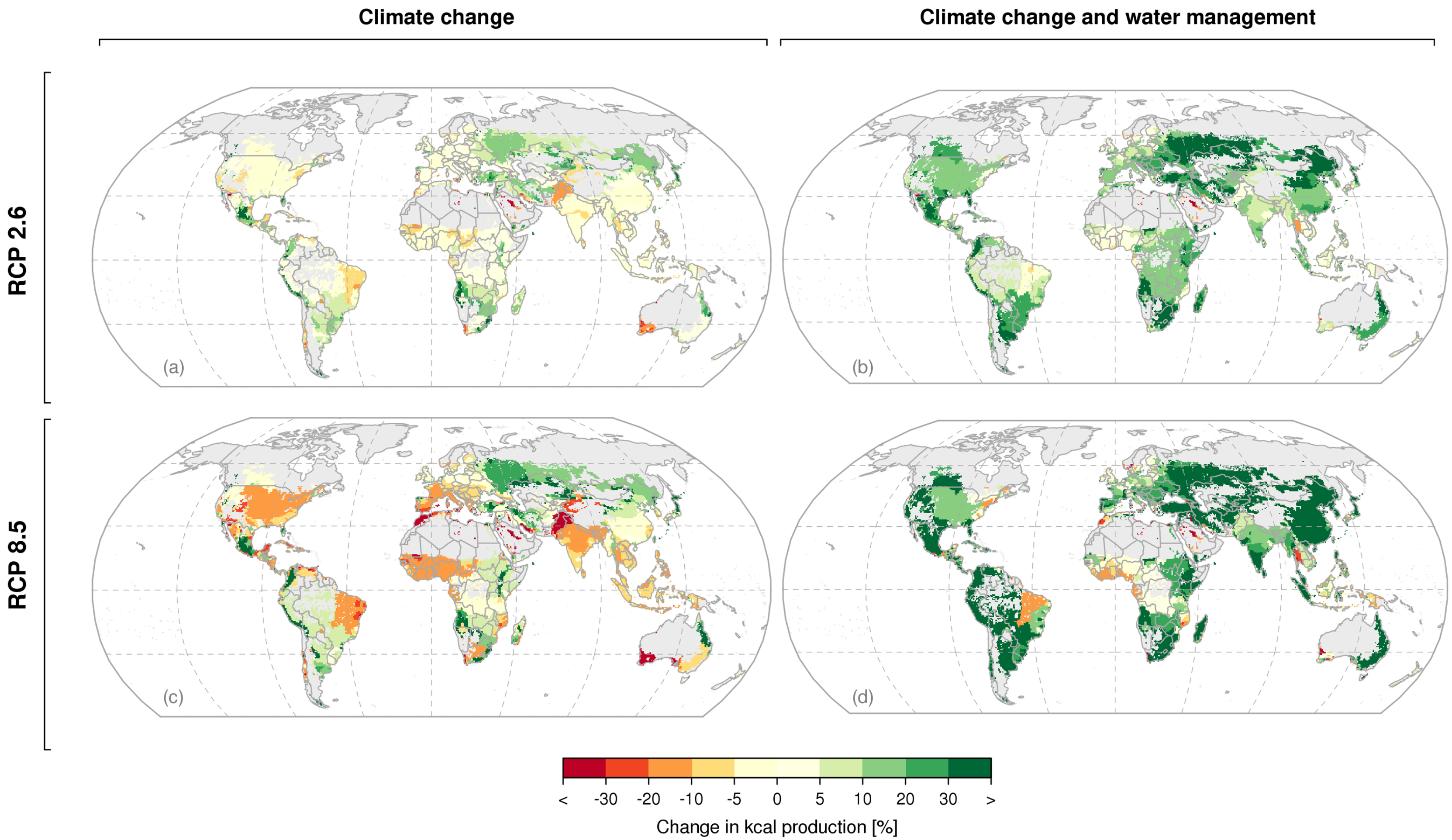

Figure 5.7.: Water management buffers adverse climate change impacts. Spatial patterns of potential climate change impact on global crop production under RCP 2.6 (**a**) and opposed to "low" water management (**b**); under RCP 8.5 (**c**) and opposed to "ambitious" water management (**d**), all for the time period 2070 to 2099 vs. 1980–2009 as averages across 20 GCMs and with "moderate" CO_2 effect (compare Table 5.4). Corresponding maps for constant and transient CO_2 are presented in Figure C.4 and C.5.

Lebel et al. (2015) simulate for maize in sub-Saharan Africa (SSA) an average yield increase with WH intervention of 9–39%. We arrive at 0-33% across SSA basins. In our simulation (50% level), on average 57 mm supplemental irrigation are applied during the growing season (in 95% of all cases less than 100 mm, Figure C.3), Fox and Rockström (2003) document 60–90 mm in a Burkina Faso case study. More generally we can reproduce the documented scale of observed yield gains using LPJmL, and our analysis extends case study insights to a broader set of climates, locations, and crops and thus refines management potentials at the global level (Rost et al. 2009).

We point out that it is critical to evaluate the local feasibility of WH catchment and storage systems. This depends on different factors (e.g. terrain type, soil structure, hydro-climatic setting, social and financial capital (Studer and Linger 2013; Falkenmark et al. 2001; Mati et al. 2007)), addressing those in detail is beyond the scope of this broad-scale study of biophysical potentials. Although case studies show that often only 10–20% of the land is unsuitable for WH and SMC adoption (Barron et al. 2015; Kahinda et al. 2008; Rensburg et al. 2012), we might exaggerate WH suitability. However, this is faced by our very conservative assumption on the catchment area that is limited to existing cropland only, and which is often much larger in reality. But it appears infeasible to delineate additional suitable catchment areas with a sufficient degree of detail globally.

Therefore, we regard the “low” and “ambitious” scenario as potentially achievable, while the “max” scenario, locally proven though, indeed appears unlikely to become implemented globally. Nevertheless, it provides important insights into planetary biophysical capacities. Furthermore, it is difficult to quantify the extent to which farmers already adopted WH and SMC measures. Although initial up-scaling projects prove successful regionally (e.g. Zhu and Yuanhong 2006), they still represent only marginal areas at the global level.

Our estimates of irrigation withdrawal and consumption agree well with previous estimates (FAO 2014b; Döll et al. 2014; Wada and Bierkens 2014), albeit featuring much more process detail. Irrigation expansion adds a noticeable share to production increases simulated in this study (Figure 5.3b, 5.5a). The expansion of irrigated crops replaces rainfed crops, which results in a propagation of irrigated cropland into pastures in some cells, as the share of irrigated pastures is generally low. However, in SSA only 5% of the cropland is under irrigation today, which first explains our flat irrigation improvement potentials in SSA (Figure 5.5b), and second outlines scope for irrigation expansion using currently untapped water resources (FAO 2005; Burney et al. 2013; Xie et al. 2014).

Finally, it is important to note that upstream IRR and WH interventions can lead to reduced return-flows and runoff, which can negatively affect water availability downstream. Despite noticeable impacts locally, gains at the basin level over-compensate losses in all basins (Figure C.4). This appears beneficial from a food production perspective, but there is a clear need for policies and institutional orders to regulate water reallocations. In this context it is crucial to quantify contributions from groundwater and water diversions, given the complex recharge and transboundary issues involved.

5.5. Discussion

This study is the first to systematically quantify potential contributions of different strategies of farm water management to increase global crop production without increasing pressure on land and water boundaries. Based on spatially and temporally detailed process-based modeling, we advance the quantification of the global achievable scope of water management in rainfed and irrigated agriculture. Simulated yield potentials are well in line with farm-level experiences, but we exploit the dynamic modeling capacity of LPJmL for complex up-scaling of water interactions to arrive at robust global estimates. 41% production growth, at global scale, released through "ambitious" water management outlines tremendous opportunities. While grand challenges lie ahead to its large-scale implementation, the "ambitious" potentials simulated here appear feasible from a biophysical and also an agronomic perspective. More than 800 million people today remain chronically undernourished (United Nations 2015b) — a kcal production gain of 40% realized by 2050 might be sufficient to halve the widening global food gap, assuming that we need 60–100% additional crop calories to eradicate hunger (a gap of 80% roughly relates to $7.6 * 10^{15}$ kcal per year, compared to the production of $9.5 * 10^{15}$ kcal in 2006 (Alexandratos and Bruinsma 2012; Searchinger et al. 2013)).

Although sustainable intensification appears high on the policy agenda, there is a lack of institutionalized water management targets. In fact, such targets are outright missing from the recently passed sustainable development goals (United Nations 2015b). Our study adds confidence that not targeting dedicated water goals means we are set to miss substantial opportunities to advance a sustainable food system and its climate resilience.

On the way toward a sustainable food future, water management is accompanied with essential co-benefits (that are not modeled here). Among the most important are reducing soil erosion through water harvesting and mulching, currently affecting ∼67% of SSA cropland (Liniger et al.

2011). But large-scale implementations of plastic mulching can also lead to environmental pollution (Liu et al. 2014). Better irrigation technology helps reducing nutrients and pesticides application (better location and timing) (Christian-Smith et al. 2012; Calderón et al. 2014), while conservation agriculture in general will help mitigate greenhouse gas emissions (e.g. Mahdi et al. 2015; Karimi et al. 2012; Liniger et al. 2011). Water management that leads to stabilized water supply throughout the growing season is prerequisite for smallholders to invest in higher inputs (fertilizer, breeds) (Biazin et al. 2012; Burney et al. 2013). Low-cost interventions (organic mulching, conservation tillage, simple drip kits) can directly translate in synergies in livelihoods; as most poor live in water-constrained agriculture, the associated scope for poverty alleviation and improved local food security is tremendous (Postel et al. 2001; Dillon 2011; Pretty et al. 2011; Kahinda and Taigbenu 2011; Burney and Naylor 2012).

At the global scale, this study suggest that both smallholder on-farm techniques and large-scale improvements of irrigation systems and WH implementation are needed, while respecting environmental flow requirements of riverine ecosystems and other environmental boundaries. Our results show that large-scale adoptions of these measures lead into water reallocations that would benefit from institutional support and water legislations as mentioned above (Molden 2007). Future investments must focus on enhancing system productivity on current arable land, integrating management in rainfed and irrigated agriculture in an integrated landscape approach (Faurès et al. 2007; Rockstrom et al. 2007). Jägermeyr et al. (2015) show that technical irrigation saving potentials are substantial at the global level, while in this study we show that such savings could be redirected to support vast currently rainfed farms with additional irrigation water. Although initial investment needs are steep, long-term economic analyses confirmed the substantial net profits achievable (Biazin et al. 2012; Fox et al. 2005).

However, water management is not a panacea and needs to be combined with other components to sustainable farm management to exploit the strong synergy between water, soil and nutrient management (Oweis and Hachum 2006). Especially in SSA, many cropping systems are highly nutrient-deficient and water management cannot fully take off, unless depleted soils become replenished (Sánchez 2010; Fox and Rockström 2003). But it is clear that the challenge of achieving sustainable food security is not only a supply-side problem. Urgent action is also needed on holding down the growth in food consumption, reducing waste, and achieve replacement level fertility (Garnett et al. 2013; Searchinger et al. 2013; DeFries et al. 2015).

5.6. Conclusion

This study quantifies the significance of integrated crop water management at the global scale to intensify rainfed and irrigated farming. Simulated measures are constrained by the assumption that pressure on water resources and land does not increase, which delineates an effective strategy to minimize agricultural impacts on the biosphere. Based on detailed, process-based simulation of underlying local biophysical conditions and with high spatio-temporal resolution, we systematically investigate scenarios of irrigation improvements and expansion, water harvesting, and soil moisture conservation. Under a "low" intensity scenario we arrive at a global kcal gain of 18%. With an "ambitious", yet achievable scenario we reveal global production potentials of 41%. Such water management interventions would also about halve the current global water gap in agriculture. Moreover, thus improved water management offers the opportunity to buffer potential negative climate change impacts in many world regions. The "low" intensity scenario might over-compensate climate change impacts under relatively low RCP 2.6 emissions (globally + 40% kcal production), while the "ambitious" scenario could ease most negative impacts in a RCP 8.5 world (globally + 33% kcal production). Such kcal gain might be sufficient to halve the global food gap by 2050. In conclusion, this study highlights that not focussing on systematic implementation of integrated crop water management means to miss substantial opportunities in intensifying global farming systems within planetary boundaries and to negotiate climate-associated risks in smallholder agriculture.

5.7. Acknowledgements

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Chapter 6.

Synthesis

This summary and perspective chapter first highlights methodological achievements (Section 6.1.1) and provides concise answers to the research questions (Section 6.1.2), before it proceeds with the discussion (Section 6.2). Therein, the significance of the main results is interpreted in the context of methodological uncertainties and the broader scientific background. Section 6.2.2 continues with a brief reflection of co-benefits and challenges of water management implementations. In Section 6.2.3, I discuss in more general terms the expected pressure on planetary boundaries by bridging the food gap without such implementations. Finally, a brief research outlook (Section 6.2.4), and a summary of the main findings with an interpretation of their potential implications conclude this thesis in Section 6.3.

6.1. Achievements

6.1.1. Methodological achievements toward the quantification of planetary opportunities in farm water management

The results of this thesis build on the development of a unique framework that advances state-of-the-art dynamic modeling capacity and allows for the first comprehensive and spatially-explicit quantification of planetary opportunities in reconciling future food production and environmental limits to freshwater use. As a central piece of investigating interactions of a comprehensive spectrum of farm water management interventions with food production, I devised and implemented a detailed representation of worldwide irrigation practices. This innovative scientific scheme allows for new insights into global irrigation performance, including adequately assessing the transboundary scope of efficiency transitions. Based on the enhanced model, I present the first gridded world map of process-based irrigation efficiencies, providing an important input for a range of other studies. As another central component of water management interventions, I developed a module to simulate the safeguarding of environmental flows needed to maintain the functioning of world river and delta ecosystems. Integrated in an internally consistent modeling framework, it lays out the much needed foundation to evaluate feedbacks — if EFR policy goals were implemented — of constrained withdrawals on water availability for irrigation and hence global food production. Since EFRs are compatible with the regional boundary for human freshwater use, this dynamic implementation also provides a framework to delineate the associated safe operating space on a detailed mechanistic basis, and thus enables to design viable pathways therein. Finally, with respect to future food production opportunities within environmental limits, I established a mechanistic representation of the most approved agro-ecological water management practices in rainfed farming. This module exploits dynamic modeling capacity to identify regions with high potential for its implementation and, most importantly, to systematically quantify complex cumulative effects of integrated farm water management in combined rainfed-irrigated systems across scales, across farming systems, and including catchment hydrology and water trade-offs, with high spatial, temporal and agronomic detail.

Although there are major simplifications and thus uncertainties associated with such global-scale quantifications, and while the realization of presented opportunities at larger domains faces non-trivial challenges, this thesis provides significant achievements toward a more sophisticated understanding of planetary opportunities in farm water management in the context of sustainable intensification of agriculture within the safe operating space for human freshwater use.

6.1.2. Answers to the research questions

Study 1: What is the water saving potential of efficiency transitions in global irrigation, without compromising food production?

Results of this study based on the new scheme suggest that out of simulated 2469 km^3/yr global irrigation water withdrawal, 51%, i.e. 1257 km^3, are consumptive use. This volume includes 608 km^3 non-beneficial consumption, which is indicative of remarkable water savings potentials. While maintaining crop production, replacing a surface system by sprinkler or drip systems could — on average — reduce non-beneficial consumption by 54 and 76%, respectively, at basin level (i.e. in account of water trade-offs). Globally, 26% of withdrawals are consumed beneficially by the crops (i.e. transpired). Regions in Central and South Asia, especially from Pakistan to northeast India and Bangladesh, and parts of Central America show particularly low efficiencies due to prevalent, less efficient surface irrigation. Europe, the Near East, and North America, but also Brazil and South Africa, stand out with irrigation efficiencies >60%, well above the global average (revised "beneficial irrigation efficiency"). Irrigation efficiency is primarily a function of management, i.e. the irrigation system in practice, but — a main finding of this study — it is as importantly governed by local biophysical conditions. Transitions in irrigation efficiency are needed most throughout these underperforming regions, and could drive water productivity increases between 20–30% at basin level.

Study 2: Where would the planetary boundary for human freshwater use be positioned, if it was based on a spatially explicit assessment of environmental flow requirements?

Toward establishing a uniform method for EFR calculations across basins, this study proposes to classify river stretches according to their flow regimes and associated EFRs, based on different hydrological methods. The conceptual review of PB-Water proposes to refine it in account of local water availability and from EFR perspective tolerable withdrawals. The protection of geographically explicit EFRs, repositions PB-Water at $\sim$2800 km^3/yr, associated with an uncertainty range of $\pm$1700 km^3/yr. The new estimate is lower then the initial marker at 4000 km^3/yr (lower end of the uncertainty range 4000–6000 km^3/yr) (Rockström et al. 2009c). In consideration of EFRs, the available global blue water declines by 36% (median of 5 methods), compared to an unrestricted scenario. Given the human blue water consumption of >1700 km^3/yr, human uses currently appropriate 61% of the tolerable volume with respect to the new mean estimate, while its lower end (1100 km^3/yr) has been exceeded already.

Study 3: If human water use was to be constrained by the EFRs, by how much and where would food production decrease?

Based on a new dynamic EFR implementation in LPJmL, results highlight that current food production heavily relies on water actually needed to sustain riverine ecosystems. 39% of current global irrigation water use (948 km^3/yr) and 22% of other uses such as industry and domestic (226 km^3/yr) occur at the expense of EFRs. If policies were implemented to safeguard EFRs worldwide, 51% of irrigated cropland would face a ≥10% production loss (affecting areas inhabited by 1.1 billion people, thereof 80% in developing countries). Amongst intensely irrigated regions, such as Central and South Asia, losses would reach >20% at the aggregated level of Food Production Units. Total global kcal production would be subjected to a 4.6% decline, corresponding to a 13.9% loss of irrigated production (total irrigation water contributes 15% to overall global kcal production). Severe hydrologic alterations occur worldwide, yet EFRs are breached most severely in large parts of Asia, the Mediterranean region, and North America — 31% of global EFR deficits occur in Pakistan alone. Further results suggest that a transition from surface to sprinkler irrigation systems (using half of thus saved consumptive losses for expansion) would suffice — at global level — to outweigh kcal losses associated with a worldwide EFR protection. Yet, 35% of irrigated cropland would remain with a ≥10% kcal loss, mostly in Central and South Asia. Although water savings potentials are shown to be significant, my results also endorse the consideration that food production reallocations might be inevitable in attaining sustainable withdrawals.

Study 4: To which extent could integrated crop water management in rainfed and irrigated farming close the future global food gap?

Results of this study indicate that ambitious water management strategies — combining interventions in irrigated and rainfed farming systems — are capable of intensifying today's global kcal production by 41% (18–60%), without appropriating additional land or water resources. Gains are most pronounced in basins currently experiencing severe water limitations, including the Middle East, Central to South Asia, North China plains, Australia, southern Africa, and the western United

States, with production increases >50% at basin level. Global irrigation improvements could save 48% of non-beneficial water consumption and thereby reduce total withdrawals from currently 2507 to 2059 km^3/yr, while in parallel redirecting water savings to put 300 Mha of neighboring rainfed fields under irrigation. Global kcal production would thereby boost by 26%. Moreover, optimizing precipitation water use through alleviating soil moisture depletion, capturing surface runoff for supplemental irrigation, and increasing soil infiltration capacity for rainfed crops, significantly shifts previously unused *in situ* precipitation toward crop transpiration, which would narrow the rainfed water gap from currently 29% to 11% and thereby increase rainfed kcal production by 25% globally (corresponding to 15% total production increase). Climate change is simulated to cause yield declines between 10–20% in many basins in Central to South Asia, the Mediterranean region, African Sahel, east of Brazil, and the United States (RCP 8.5, median of 20 GCMs), while other regions face increases to a similar extent (parts of Russia, east and southern Africa, and Central and South America). My results indicate that water management can buffer adverse climate change impacts in many regions, while maintaining the global yield-increasing management potential (net effect of water management higher under climate change impact). At global level, water management is simulated to increase kcal production by >40% under all but the RCP8.5 climate change scenario (still +35% kcal). Assuming that global food production must be increased by 80% (60–100%) to end hunger by 2050, such opportunities might be sufficient to halve the global food gap on a sustainable basis.

6.2. Discussion

6.2.1. Significance of the results

The outcome of this thesis can be grouped into two primary lines of achievements. First, a challenge for future farming systems: EFR transgressions outline water overuses that need to be reset to safeguard aquatic ecosystems, with associated feedbacks on agricultural productivity. Second, farm water management as an opportunity: Yield-increasing and water-saving capacities in irrigation systems and agro-ecological practices such as organic mulching and rainwater harvesting need to be mainstreamed. In the following, I further contextualize the key findings, from EFR challenges, over opportunities in irrigation, to opportunities in rainwater management.

The challenge of environmental flows

Local holistic methods to the comprehensive determination of EFRs are — albeit inevitable for effective implementations (Poff and Zimmerman 2010) — unsuitable to provide timely global coverage, owing to financial, institutional, and methodological challenges. Given that many legislations already developed are not yet being implemented (see Section 6.2.2), Pahl-Wostl et al. (2013a) recently highlighted the need for systematic approaches at larger domains and, in particular, on the interaction between social and environmental systems, such as food production. Simpler hydrologic EFR approaches are suitable for river sustainability planning as first order estimates for flow allocations across regions. To this end my results are in direct support. I advance the quantification of environmental flows worldwide, by reflecting methodological uncertainty in systematic EFR allocations based on a global agro-hydrological modeling framework. At a yet simplified but robust basis, the results indicate that 39% of global renewable freshwater withdrawals for irrigation occur at the cost of EFRs and are thus unsustainable. While EFR estimates agree well with local field studies (compare Figure 4.4), they are difficult to compare across other studies at larger domains, because EFRs have rarely been implemented in grid-based hydrological models in a mechanistic way (e.g. Smakhtin et al. 2004; Hanasaki et al. 2008). Steffen et al. (2015) and Pastor et al. (2014) calculate EFRs based on hydrological methods (similar to the ones used in Chapter 3 and 4) in model post-processing (i.e. not in feedback with other processes such as irrigation), yet they present very similar spatial patterns of global EFR transgressions as shown herein (Figure 4.1).

To my knowledge, there is no approach available that investigates the feedback of EFRs on food production systems based on a dynamic model implementation. Yet, Bonsch et al. (2015) examine the effect of protecting EFRs on agricultural withdrawal and suggest only moderate effects at global scale, but their analyses incorporates EFRs as exogenous factor, aggregated to annual sums and large world regions, neglecting temporal and geographical pattern. This is contested by Strzepek and Boehlert (2010) (with a simplified basin-level approach using Smakhtin et al.'s Q90 method), who conclude that EFRs pose a greater challenge for agricultural water availability than climate change-related alterations of the discharge regime. My results, based on robust and process-based dynamic feedbacks of EFRs and irrigation, also provide evidence that water reallocations needed for safeguarding EFRs significantly affect global food production. Half of globally irrigated area would face a production decline of at least 10%, some basins, e.g. in Central Asia, show kcal declines >30%, affecting 1.1 billion people. This shows that sub-regional effects and inter-annual flow variability are particularly important to account for. Since such a reduction of irrigation potential impairs aspirations of food security and may have adverse effects on food prices (Fraiture and Wichelns 2010), it is particularly important to assess the coupled feedback of irrigation improvements paired with protecting EFRs, to provide the knowledge needed for designing viable water management strategies in the vein of targets such as proposed in the Brisbane Declaration and now the SDG agenda (Pahl-Wostl et al. 2013b; Brisbane Declaration 2007; United Nations 2015a) (see next section on irrigation).

EFR estimation herein is founded on a conceptual basis and includes limiting factors, such as water quality, channel and habitat maintenance floods, and non-renewable groundwater abstractions that are beyond the scope of this work and not simulated. Furthermore, overall uncertainties accumulate from uncertainties in the precipitation input (Wada et al. 2014), LPJmL limitations in simulating river flows, and uncertainties in the EFR calculation method. In the end, EFR calculation methods aim at reaching a "fair" ecological status, which is a conservative assumption as this status can still be characterized by disturbed biota, loss or reduction in spatial distribution of sensitive species, and occurrence of alien species (Smakhtin et al. 2004). These simplifications and uncertainties require refinements through comprehensive local and regional assessment and monitoring programs. Nevertheless, such hydrological, conceptually simple, "percent of flow" approaches prove instrumental for the determination of EFRs at larger scales and could provide already a high degree of protection for natural flow variability when implemented (Richter et al. 2012). Provisional EFR estimates of this kind, now operationalized in the agro-ecological modeling framework LPJmL, are valuable for trade-off analyses and for stimulating and focussing of discussions concerned with the quantitative substantiation of policies at larger domains, such as SDG targets (detailed in Section 6.2.2).

Opportunities in irrigation

In view of opportunities in agricultural water management, the mechanistic simulation of irrigation performances of the world's major crop types with explicit representation of underlying biophysical processes, including factors such as climate, and soil hydraulic conductivity, and most importantly management properties, significantly advances the global quantification of irrigation performances and refines earlier estimates based on much less detail-depth (e.g. Brouwer et al. 1989; Rost et al. 2008b; Sauer et al. 2010). To overcome older confounded concepts of irrigation efficiency (e.g. Bos and Nugteren 1990), I advocate a proactive revision: "beneficial irrigation efficiency": beneficial consumption (i.e crop transpiration) by withdrawals, to actually delineate savable and non-savable flows within ET (total consumed irrigation water). In turn, I contribute to the discussion on water saving potentials of irrigation systems, as the process-based modeling herein shows that ET does not fall in a one-to-one relation with crop growth, as it is often claimed (e.g. Perry et al. 2009). I disclose clear manageable saving potentials (Figure 2.8): globally about half of consumed irrigation water is non-beneficially lost (again, return flows not considered). Thereof, feasible irrigation transitions could save again about 50% ("best practice" scenario in Chapter 5), highlighting that roughly 25% of global irrigation water can be considered savable, while maintaining yield levels. Central to South Asia show highest saving potentials and contribute to large parts to the globally weak irrigation performance.

Water saving potentials are important to evaluate with respect to current water over-exploitation. My third study (Chapter 4) highlights that saving potentials could be substantial enough to outweigh adverse effects of EFRs on irrigated food production at global scale. However, there are regions, most notably the Indus river basin in Pakistan, that heavily rely on unsustainable withdrawals beyond the scope of irrigation efficiency improvements. Especially in Central to South Asia, production reallocations appear inevitable to attain sustainable withdrawals (SDG target 6.4.). In this context, it is important to stress the need for effective water policies, as water reallocations are difficult and farmers do not invest in better irrigation technology to protect ecosystems, but for profit (Ward and Pulido-Velazquez 2008) (detailed in Section 6.2.2).

In terms of food production, irrigation improvements do not translate directly into higher yields. This is explained by the fact — on global average — that irrigated systems generally do not operate under water limitation (yet clear spatial pattern, see Figure 2.2). The key message is, the yield-increasing potential of irrigation transitions is located on the neighboring underperforming rainfed field, if water savings (beyond ecosystem needs) were redirected there. With such an integrated view on combined irrigated-rainfed systems, efficiency transitions in irrigation reveal tremendous opportunities for sustainable intensification, affording to increase irrigated area to a total of 600 Mha and thereby increasing total global kcal production by 26%.

Critical limitations include that LPJmL is not yet capable of representing interactions with non-renewable groundwater resources, Wada et al. (2012) suggest that such would contribute $\sim$20% to the total irrigation water demand. The model also treats only ocean outflows as non-accessible return flows, while fractions of seepage and runoff losses, often affected by degraded water quality, might not be recoverable with reasonable technical and economic effort (compare Figure 2.1). Although my work advances the information on global distributions of irrigation systems, subnational assumptions are rough and employed data incomplete. Input data improvements (spatial and crop-type distribution of irrigation systems) would noticeably enhance overall results of irrigation transitions (further limitations are discussed in Chapter 2). Yet, biophysical irrigation processes and resulting water flows are simulated with a high degree of detail. Sensitivity analyses and correlation analyses of dependencies on biophysical factors suggest that the representation of irrigation practices is reasonable from a biophysical and agronomic perspective, while the evaluation against other estimates of irrigation efficiency shows good agreements (Section 2.4.4).

After all, this innovative irrigation scheme lays the foundation for a series of important future studies, including refined assessments of climate change impacts on irrigation requirements and water trade-off analysis in view of sustainability targets. My pilot analyses suggest that opportunities in irrigation improvements might be more substantial than often anticipated, and that they should be considered an important means on the way toward sustainable farming systems (see Section 6.2.2 for implementation challenges).

Opportunities in rainfed farming

Rainwater management interventions are much less discussed than irrigation among scholars, stakeholders, and politicians (e.g. Falkenmark et al. 2004; Rockström and Falkenmark 2015), and not systematically assessed regarding its role in closing global yield gaps. Mechanistic simulations herein indicate that measures such as rainwater harvesting, mulching, and conservation tillage could increase total kcal production by about 15% (equalling +25% rainfed production), which is substantial given the current overall irrigation contribution of 15%. Using a similar modeling approach, Rost et al. (2009) find that such measures increase global net primary production by 19%. Lebel et al. (2015) simulate water harvesting to increase maize yields in SSA by 9–39%. My results show 0-33% increase across SSA basins, providing on average 57 *mm* supplemental irrigation, while Fox and Rockström (2003) document 60–90 *mm* in a Burkina Faso case study. In general, I can reproduce the scale of documented case study observations using LPJmL, and thereby extend the evaluation of yield-increasing potentials of on-farm rainfed water management to a broader set of climates, locations, and crops, which eventually allows to quantify opportunities at the global level.

Water-constrained rainfed agriculture is particularly vulnerable to climate change, for example, due to longer and ill-timed intra-growing season dry spells (Barron et al. 2003; Lobell et al. 2008). This is in agreement with my results, as they exhibit strong negative climate change impacts on already low-yielding rainfed systems in the West African Sahel (see Figure 5.7). Yet, soil moisture conservation practices could improve kcal production particularly in these regions by 20–30%, while water harvesting techniques show yield-increasing patterns between 10–20% more widespread across SSA. Case studies confirm these opportunities to cope with dry spells, but to tackle longer droughts, more costly strategies such as irrigation are needed (e.g. Laube et al. 2012). In comparison, overall potentials associated with rainfed water management are 11% below those of expanding irrigation by efficiency improvements, globally. This is to be expected, as average irrigated yields are higher than rainfed yields, e.g. by the factor ∼1.7 for cereals (Siebert and Döll 2010). However, it does not hold true uniformly, and not necessarily in the regions of the poorest. In SSA, for example, irrigation improvements cannot contribute much, as only 5% of the cropland is irrigated. This gives reason to Rockström and Karlberg (2010) to call for a "triply Green Revolution" that not only intensifies food production aligned with environmental concerns, but that "invests in the untapped opportunities to use green water in rainfed agriculture as a key source of future productivity enhancement".

With the focus on SSA as a potential hotspot for agricultural contributions to food security, it is important to note that water management interventions in this study occur under co-limitation by nutrient availability. While other region appear to exhibit even larger yield-increasing potentials associated with optimizing precipitation water use, e.g. the Indus Basin (Figure 5.6), they are generally also associated with higher nutrient inputs (e.g. Mueller et al. 2012). Nutrient limitation is a major factor to prevailing low yields in SSA (Sánchez 2010), and LPJmL simulations confirm that net water management potentials rise, when nutrient deficiencies are defeated (not shown). However, it merits refined investigations of feedbacks from nutrient limitation (which is currently insufficiently accounted for in LPJmL through country-level estimates of management intensity) to here simulated water management opportunities, to confirm that suggested potentials can be realized without significant additional fertilizer input.

Climate change is simulated to impact global kcal production between -18% to +13%. While future precipitation patterns are uncertain, CO_2 fertilization is currently the largest sources of uncertainty in the assessment of climate change impact on crop growth and quality (Rosenzweig et al. 2014). LPJmL simulates its potential (i.e unconstrained) effect, feasible in experiments, but likely not to be realized at global level due to limitations such as nutrient availability and soil degradation (Ainsworth et al. 2008). Further uncertainties are discussed in Chapter 5.

Significance of global modeling

Case study observations document the increasing scale of successful implementations of integrated soil and water conservation methods with multiplicative positive effects on crop yields and ecosystems. Pretty et al. (2006) and Pretty et al. (2011), for instance, testify an average >2-fold yield increase across >12 Mha farmland in Africa. To the same end, a recent World Resource Institute report (Searchinger et al. 2013) emphasizes the importance of integrated water management in the context of sustainable intensification. Now the modeling-framework developed in this thesis provides the platform to scale such proposals to global coverage and evaluate the integral potential in the light of biophysical potentials. Combining irrigation improvements and expansion with the most approved measures in optimizing the use of precipitation water, into an integrated rainfed-irrigated farming system, reveal global food production possibilities of 18–60% resulting from better water management on current land. Given the assumption that food production might have to be increased by 80% through 2050, and in comparison with other measures available to intensify the global food system (Section 6.2.3), these opportunities appear tremendous. This is a novel insight and advances the scientific knowledge of the realm biophysical food production opportunities on a sustainable water basis.

LPJmL seems appropriate to the question at hand and a global 0.5 grid provides adequate resolution. Figure B.5 provides compelling evidence for LPJmL's capability of representing observed water stress effects on crop growth, which is key to explaining yield variability and thus feedbacks from water management on food production levels. Nevertheless, evidence based on global-scale modeling studies of this kind must be interpreted carefully. As outlined above, uncertainties accumulate from different sources, including precipitation data, land use data, and model formulations (compare e.g. Haddeland et al. 2011). Yet, while each domain (EFRs, irrigation, rainfed options) merits refinements in follow-up studies, the essence is represented to a degree that allows to couple them to an operative integral model. Thereby produced results can define the biophysical realm of possibilities, but are far from local applicability. That said, such global picture can capture complex feedbacks, reveal the scale of management interventions, and highlight systemic opportunities at regional to global scale. While important to understand Earth system functioning, such global-scale modeling can also provide cost-effective and flexible approaches in assistance of international decision making (Matthews et al. 2012), as particularly needed in the process of developing the ambitious but unspecified SDG water-food agenda (see Section 6.2.2). However, such evidence lays out the broader outlines of a knowledge base only, and must be combined with finer-scale research to inform local needs and potential adaptive solutions (De Fries et al. 2012; MacDonald et al. 2016). Results presented here should be evaluated regarding local feasibility, including factors such as terrain type and social and financial capital (Liniger et al. 2011), and complemented by independent approaches (e.g. Arthington et al. 2006; Poff et al. 2010; Pahl-Wostl et al. 2013a).

6.2.2. Co-benefits of water management and barriers to implementation

Additional benefits

The adaptation to higher efficient agricultural water management and the implementation of water targets both face challenges but also positive externalities beyond yield increases and water savings, especially for developing countries. Improved irrigation systems can have additional benefits, such as improved crop quality, reduced nutrients and pesticides application, and reduced water logging (Gleick et al. 2011; Calderón et al. 2014). Water harvesting and mulching can reduced soil erosion, an important factor currently affecting ∼67% of SSA's cropland, and help controlling weeds, while conservation agriculture in general will help mitigate greenhouse gas emissions (Liniger et al. 2011).

Water management that leads to stabilized water supply throughout the growing season increases resilience to erratic rainfall and climate change (FAO 2014a; Nicol et al. 2015). As probably the single most important externality, it can thus expand economic opportunities, and is often a prerequisite for smallholders to invest in higher inputs such as fertilizer or irrigation (Conway 1999; Biazin et al. 2012; Burney et al. 2013). Low-cost interventions such as organic mulching, conservation tillage, and simple drip kits, can catalyze a shift past low input-output systems and directly translate in synergies in livelihoods (Postel et al. 2001; Kahinda and Taigbenu 2011). Given that most poor live in water-constrained agriculture, the associated scope for poverty alleviation and improved local food security is tremendous (Dillon 2011; Burney and Naylor 2012; World Water Assessment Programme 2015b). Generally, economic growth in the agricultural sector in developing countries is found to be more effective in reducing poverty than GDP growth in other sectors (Tony Elumelu Foundation 2016).

Challenges and policy implications

Implementing large-scale shifts in crop water productivity and safeguarding EFRs alike, creates substantial economic, political and social burdens. Promising examples exist, proving instrumental in technical feasibility, but the challenge is to spread effective mechanisms to farmers and stakeholders around the world (Pretty et al. 2011; Le Quesne et al. 2010). Despite the recognition that judicious water management can ease challenges in the semi-arid developing world (e.g. Falkenmark et al. 2009), policy impediments have delayed a scale-up of related technologies (Merrey and Sally 2008). While the UN and World Bank initiate action in support of water for sanitation, similar is lacking to promote farm water management, and to advocate its financing and implementation. This is particularly important for interventions in rainfed systems, as they are largely neglected in current development strategies (Rockström and Falkenmark 2015). Incentive-based instruments for water management (The Rockefeller Foundation 2015), including water funds, can assist farmers to identify and apply best-practice management regimes in the context of socioeconomic, technical and agro-ecological environments (Nicol et al. 2015; Goldman-Benner et al. 2012). A collaboration between researchers and farmers in rural China recently highlighted again that knowledge transfer is a central aspect of local solutions (Samberg 2016). Gleick (2003), promotes “soft-path” solutions, where small-scale decentralized projects complement well-planned centralized infrastructure, in favor of broad-based water productivity improvements, but implementing such ideas at larger domains requires a complex combination of large investments, institutional water policy regulations, and cultural changes.

New investment needs are substantial, and smallholder rainfed farming might have to bare the heaviest burden in achieving the SDG hunger target. Capacity development, planning and infrastructure development for small-scale water harvesting systems are associated with investments of around US$10–20 billion per year for 10–15 years, which is comparable with those for basic sanitation, infrastructure, and water supply (Rockström and Falkenmark 2015). Although initial costs are large, long-term economic analyses confirmed the substantial net profits achievable (Biazin et al. 2012; Fox et al. 2005). Foreign investments can be beneficial, but must be regulated to ensure the benefit of people (D’Odorico and Rulli 2013), while smallholders should be integrated into value chains to maintain their competitiveness (Pingali 2012). Agricultural export subsidies also contribute to prevailing low productivity in the developing world (reflected in SDG 2, (United Nations 2015a)). Underlying institutional weaknesses link to poor access for smallholders to credit and insurance, but equally important, to infrastructure and markets (Rosenzweig and Wolpin 1993; Foresight 2011; Descheemaeker et al. 2016).

The transboundary implementation of policies to attain sustainable freshwater withdrawals worldwide provides a severe challenge. Although recognized as legitimate water users within the Integrated Water Resources Management (IWRM) context (e.g. Naiman et al. 2002), the EFR concept has not gained political momentum needed to ensure environmentally sustainable basin management in competition with other water users like agriculture and industry (Poff and Zimmerman 2010; Le Quesne et al. 2010). This is explained by the prevalence of specific case-study assessments and the lack of global scale analyses (one of the motivations to this dissertation), paired with limited understanding of EFR governance (Pahl-Wostl et al. 2013a). Water governance is needed to allocate water resources to high-value uses and to balance priorities amongst competing demands (World Water Assessment Programme 2015b; Hoekstra 2011; Falkenmark et al. 2007). For instance, most economic models are yet to value the services provided by freshwater ecosystems (World Water Assessment Programme 2015b). Especially economic incentives through intelligent water pricing can trigger investments in better technology and can help achieving trade-offs at basin level (Molle and Berkoff 2007; Ward and Pulido-Velazquez 2008). However, allocating water to different uses and users is delicate, given its conflict potential. It requires clear water targets and flexible and adaptive institutions including laws, but also societal norms that are changing during processes of social learning (Pahl-Wostl et al. 2013a). There are positive examples, e.g. in the USA (Kendy et al. 2012) or China (Zhang et al. 2012), but water management practices are often fragmented, leading to lost synergies, poor trade-offs, and are not readily transferable (UNEP 2011). Therefore, transboundary and cross-sectoral collaboration must be strengthened, by regulatory measures from converging national policies, supported by global water governance (Vörösmarty et al. 2015; Hoekstra 2011). Many established environmental flow provisions remain at the stage of policy rather than implemented, which is eventually justified by a lack of political willpower and transboundary cooperation (Le Quesne et al. 2010).

A critical issue to water governance is setting strategic goals, now for instance formulated in the SDGs. They represent an essential framework to catalyze and direct needed regulatory efforts, but lessons learned from the MDGs show that setting goals is not enough, it requires specific and actionable targets to turn this vision into action (United Nations 2016b; Pahl-Wostl et al. 2013a). Specific water targets and monitoring indicators were rendered in proposals to the SDGs, but insufficiently implemented in the final resolution (Griggs et al. 2014; Bhaduri et al. 2016). Many of the indicators related to the agriculture and the environment (e.g. “area under productive and sustainable agriculture") are not precisely defined, not quantified, and eventually considerably more vague than those linked to social targets (ICSU 2015). Yet, all SDG targets related to sustainable intensification of agriculture (SDG 2.3, 2.4) and sustainable water management (SDG 6.4, 6.5, 6.6), are being labeled with the "red traffic light", indicating that they are insufficiently developed and require significant work (ICSU 2015).

To that end, my results provide insights that could contribute to this discussion in two aspects: First, with the assessment of sustainable food production opportunities related to water practice, results highlight the overall scale of biophysical possibilities and thus help to shift attention to currently neglected farm water management in the context of target 2.3 "double agricultural production" and target 2.4 "ensure sustainable food production systems". Second, since EFRs are a pivotal component of attaining target 6.4 "sustainable withdrawals", they can quantitatively contribute to the discussion on formulating more specific and, down the line, actionable targets. As a key aspect therein, they highlight the significant interaction of these targets, i.e. EFR feedbacks on food production.

In summary, this section highlights that the research provided throughout this thesis provides the foundation to consider how opportunities in a sustainable transition of agriculture might link to broader social-environmental systems across scales. From local impacts at the smallholder level with considerations of e.g. farm size and capital costs, to basin-level water and land trade-offs along the river network (e.g. land requirements for water capturing and storage), to transboundary requirements of institutional support and water governance. While basic water management practices such as mulching, water harvesting, and also simple drip systems can largely be made accessible to smallholders (Postel et al. 2001), to attain the full opportunity spectrum, more coordinated and commercialized transformations of farming systems might be required, as current farm sizes with <10 ha prevail in those regions exhibiting largest potentials (Graeub et al. 2016). Adaptive solutions require future research related to all of these interactions (MacDonald et al. 2016).

That said, when weighing the large upfront capital costs carried by the implementation of proposed water management interventions, it is important to account for the costs not to take action. Degrading ecosystems can be of substantial value (Poff et al. 2015), Costanza et al. (2014) aim to express disappearing wetlands in monetary terms and estimate that between US$3000 to US$10,000 billion per year worth of ecosystem services were lost from 1997 to 2011.

6.2.3. Closing the food gap within PB-Water and PB-Land: further simulations

Closing the future food gap — i.e. increaseing today's food production by ∼80% (see Section 5.5) — by means of irrigation and cropland expansion, would put heavy pressure on PB-Water, but also on the planetary boundary for land-system change (PB-Land). PB-Land is positioned at a forest-loss level of 25% globally (area-weighted forest biome average, see Steffen et al. 2015), which is already transgressed today at 30% (own calculations, confirming Steffen et al. (2015)). Based on today's irrigation systems prevalence and remaining arable land, substantial and new blue water (irrigation expansion) and green water (land expansion) requirements would be needed to increase overall food production to the amount required by 2050. An initial estimate is set at 5200 km^3/yr (SEI 2005). For the spatially explicit assessment of resulting potential threats to the status of PB-Water and PB-Land, I conducted additional LPJmL analyses[1] in this chapter. Results suggest that closing the demand merely through new land appropriations (irrigation unchanged), rainfed cropland would have to expand by 78%, resulting in a global forest loss of 70% and a major onward transgression of PB-Land (Figure 6.1). Alternatively, closing the demand merely with new blue water resources (total cropland extent unchanged), freshwater use for irrigation would explode from currently 2400 to 8000 km^3, resulting in a devastating transgression of PB-Water[2]. These numbers showcase the severe threat to planetary boundaries and thus Earth system functioning under the most unfavorable assumptions. Still, closing the food gap through a combination of cropland expansion and irrigation expansion, based on today's water productivity, would substantially breach both boundaries, at 50% forest loss and 6200 km^3 freshwater use (Figure 6.1, Table 6.1).

Further results form these new simulations indicate that the rigorous implementation of farm water management interventions, as detailed in Chapter 5 ("ambitious" scenario), could substantially relieve pressure from both boundaries. Simulations suggest that water management interventions

[1]Land and freshwater requirements to increase current kcal production by 80% under current management practices are calculated constrained by available arable land and renewable surface water. Climate input and model setup is as in Jägermeyr et al. (2016). To realize cropland expansion, the current extent of rainfed farmland is gradually expanded in adjacency of existing agricultural land, prioritizing cells with lower water limitation, until the demand is met at global level. Pastures are expanded likewise, as the diet composition is assumed to be fixed. Irrigation is not expanded to keep the status of PB-Water unchanged. As for blue water expansion (constant extent of total cultivated land), irrigation is gradually expand into rainfed cropland (using the country's dominant irrigation system) in cells with available discharge, prioritizing cells with higher water stress, until the demand is met at global level.

[2]Note that for reasons of comparability with the original planetary-boundary diagram (Rockström et al. 2009c), throughout this analysis PB-Water is positioned at its initial estimate of 4000 km^3/yr and human freshwater use is defined as LPJmL-simulated irrigation withdrawal, at currently ∼2400 km^3/yr, to be comparable with the ∼2600 km^3/yr in Rockström et al. (2009c). See also the discussion in Section 6.2.4.

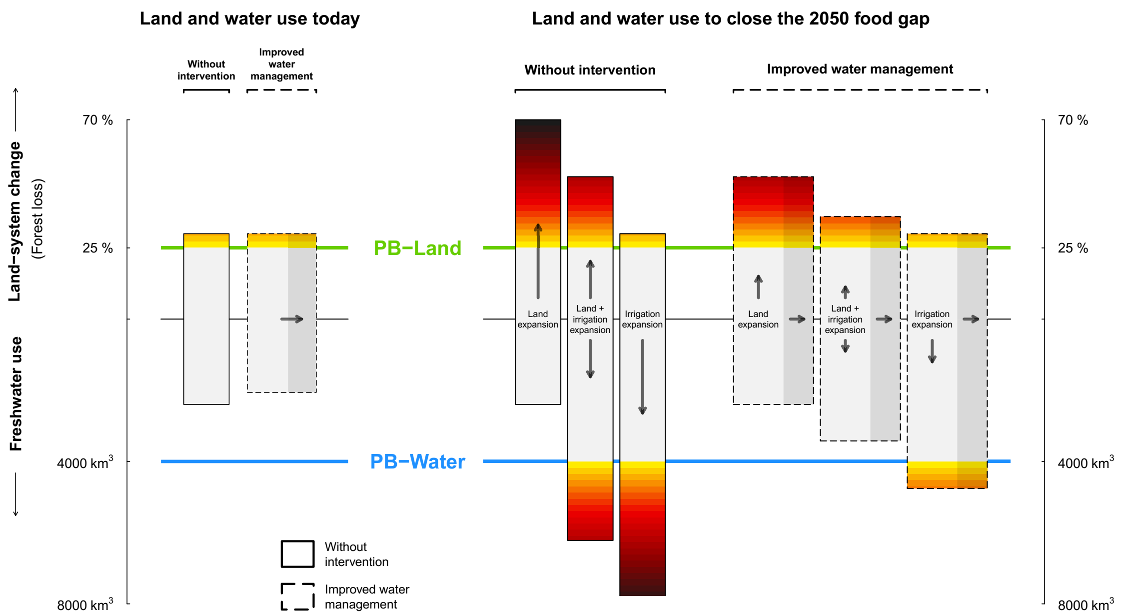


Figure 6.1.: Improved water management relieves pressure from the planetary boundaries. The status of PB-Land (25% forest loss) and PB-Water (4000 km^3 water use) is illustrated as a function of cropland extent for food production today, and in 2050 assuming to close the food-gap (+80% kcal), respectively with and without water management interventions. Future food demand is exemplarily met by expansion of either cropland expansion, a combination of cropland and irrigation expansion, or irrigation expansion. Stack areas scale proportionally with kcal production (compare Table 6.1).

can strongly reduce land and water requirements, and help closing the food gap at 3400 km^3 freshwater use, and 36% forest loss, charging more modest forms of irrigation expansions and cropland expansions (Figure 6.1, Table 6.1). While PB-Land would be further transgressed by 6% in this scenario, PB-Water remains untransgressed.

Although this theoretical off-the-cuff assessment bears uncertainties in many respects, these analyses (Figure 6.1) convey a robust message: Farm water management, as represented here, is not sufficient to manifest future food production within the safe operating space of both freshwater use and land-system change. The required expansion of cropland or irrigation would transgress either PB-Land or PB-Water, which confirms conclusion from SEI (2005), suggesting that even 1000 km^3 from rainwater harvesting are not sufficient to produce the amount of food required and might lead to additional land expansion. However, the key message is that water management interventions constitute a major factor in relieving future pressure from land and water resources and can help

Table 6.1.: Future food gap puts pressure on planetary boundaries. This table shows changes in freshwater use (PB-Water), irrigated area, cultivated area, and forest loss (PB-Land) as a function of cropland extent for food production today, and in 2050 assuming to close the food gap (+80% kcal), respectively with and without water management interventions (illustrated in Figure 6.1). Future food demand is exemplarily met by expansion of either cropland expansion (Land), a combination of cropland and irrigation expansion (Land + water), or irrigation expansion (Water). These numbers are based on spatially explicit simulations with LPJmL. Note that freshwater use relates to irrigation water withdrawal.

	Today		**Requirements in 2050 (+80% kcal)**					
Water management	current	improved	current			improved		
Means of expansion	–	–	Land	Land + water	Water	Land	Land + water	Water
Freshwater use [km^3]	2400	2100	2400	6200	8000	2100	3400	4800
Irrigated area [Mha]	300	600	300	2000	1800	300	1500	2200
Cultivated area [Mha]	4300	4300	7600	6500	4300	5900	4800	4300
Forest loss [%]	30	30	70	50	30	50	36	30

reducing the risk of (further) transgressing PB-Land and PB-Water. The other way round, closing the food gap without rigorous focus on farm water management contributions might be infeasible, while staying within environmental limits. These results are also in line with Hayashi et al. (2013), suggesting that the world's water-stressed population will increase to about 3.3 billion in 2050, without the implementation of water management options, especially irrigation improvements.

Recent studies also propose other viable measures to relieve pressure from land resources in closing the food gap, for example, by increasing cropping intensity and spatial reallocation (Ray and Foley 2013; Mauser et al. 2015), or by increasing trade volumes (Erb et al. 2016; Billen et al. 2015). Freshwater resources and water management are however neglected therein. The comparative scale of water management interventions must be highlighted in future studies, as they are largely underrepresented in current research and development strategies (see also Section 6.2.2).

In the end, closing the food gap is not only a challenge to food supply — it is also an equity challenge. The fact that 800 million people remain undernourished is not the result of biophysical limits, but of social and institutional failures to implement solutions (Sánchez 2010). It entails complex factors to provide accessibility to food at different scales, including purchasing power and equitable distribution (Loos et al. 2014). On the other hand, effective measures are also needed to minimize the growth in food consumption, including food waste reduction, diet changes, and

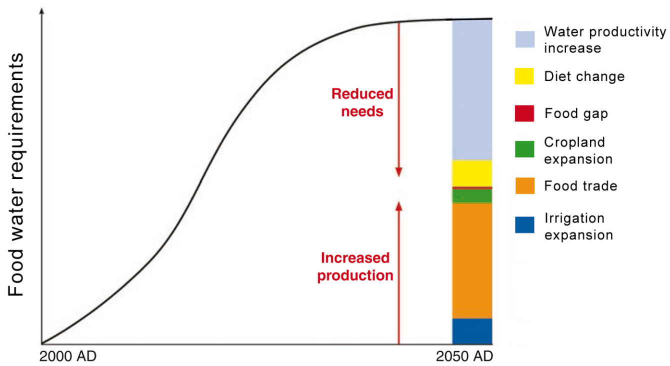


Figure 6.2.: A vision for closing the global food gap. This theoretically viable pathway to provide water requirements for future food needs through 2050 highlights that a portfolio of different measures is required (adapted from Falkenmark and Lannerstad (2010)).

targeting replacement level fertility (e.g. Garnett et al. 2013). Food losses contribute about 25% to current demand (Kummu et al. 2012). Reducing animal proteins in human diets, especially those originating from beef, is also associated with substantial potentials to reduce water and land requirements (Kastner et al. 2012; Cassidy et al. 2013) — e.g. irrigation water consumption by as much as 14% (Jalava et al. 2014). Measures targeting population growth remain politically delicate, as demonstrated by the controversial public reaction to the recent Club of Rome report (Maxton and Randers 2016). Not least, food trade, comprising virtual water trade, is an important global factor to close the food gap, as it can significantly reduce nations' dependency on local water resources, but it may also be a driver to further exploit local water resources for export (e.g. Hoekstra and Mekonnen 2012; Fader et al. 2013).

An illustration of a potentially viable pathway combining various proposals to meet the global water requirements for future food production is shown in Figure 6.2. Many of these measures addressing sustainable intensification of the food system have been studied, but generally assessed isolated from each other. In order to understand the integral potential of sustainable intensification, all available options need to be studied in a combined way to reveal both synergy effects and overlaps, which is the main conclusion of an initial study in that direction that I co-authored (Kummu et al. 2017, currently in review).

6.2.4. Research outlook

There are many avenues of important open research questions to advance and complement the results of this thesis. For instance, the irrigation expansion potential beyond saved water from existing systems is not studied here. Despite the over-exploitation in many world regions, there are substantial untapped freshwater resources available, in the first place, in SSA with only 5% of cropland currently under irrigation and only 3–5% of the potential water resources are developed (FAO 2005; Neumann et al. 2011; You et al. 2011). But in this context it is also important to evaluate feedbacks of large-scale irrigation expansion on environmental processes beyond water scarcity, e.g. extended moisture recycling and surface cooling might affect monsoon functioning (e.g. Siebert et al. 2015). Moreover, impacts of water quality degradation as a non-consumptive factor are important but largely neglected in current global agro-hydrological modeling. Especially in the context of land-use-related water management, there is little understanding of current degradation levels und associated management opportunities (e.g. Mekonnen and Hoekstra 2011; Bogardi et al. 2013).

More work is needed to identify how the water management potentials at global scale interact with cross-scale linkages at farm, basin, and regional level. For example, how might water management interventions affect global food trade patterns? Difficult food production reallocations need to be assisted by more in-depth water trade-off analyses, including deficit irrigation, and optimization of water allocations. A key next step is also to develop and disentangle location-specific solutions to scale sustainable intensification based on farming system characteristics (e.g. Barron et al. 2015). Incorporating such linkages and trade-offs in future research is needed to develop adaptive pathways (MacDonald et al. 2016).

Generally, much research is currently focussed on identifying problems, more solutions-oriented approaches are required to explore opportunities and to devise viable pathways within the safe operating space (Pahl-Wostl et al. 2013b; De Fries et al. 2012). However, there are two general issues linked with planetary boundary concept that need to be solved by future research. First, most boundary definitions remain premature and, second, they are not independent, which affects the characteristic of the safe space — both must be understood as a precondition to developing realistic pathways.

The revision of PB-Water in Chapter 3 enhances the credibility of its preliminary estimate, as it is now based on context-specific EFRs indicative of ecosystem water needs, calculated with a spatially explicit agro-hydrological modeling framework. While the calculation of different EFR methods proves instrumental to approximate the regional boundary, PB-Water remains provisional, pending further refinements and constraints such interactions with other boundaries and cascading impacts on large-scale Earth system properties.

The most important caveat is the large uncertainty associated with global water availability and global human water use, which directly affects the positioning of PB-Water. Rockström et al. (2009c) employ an estimate for human freshwater consumption of 2600 km^3/yr (adopted from Shiklomanov and Rodda 2003), while other estimates are much lower: ∼1700–2270 km^3/yr (Wada et al. 2011; Hanasaki et al. 2010), including LPJmL simulations (1270 km^3 for irrigation + 200 km^3 for other uses + ∼20% from nonrenewable groundwater $\simeq$ 1800 km^3). These large uncertainties are sensitive and refinements are needed, also in respect to water accessibility (remote flows, inaccessible flood water). Not least, there are reasons to argue that environmental limits to human freshwater use must be based on withdrawals, not only on consumption, as inaccessible, degraded, or time-lagged return flows impair the ecosystems status. Moreover, land-system change and climate change affect global water availability, but such linkages to the status of PB-Water are only crudely understood.

Because water availability and depletion is a local challenge in the first place, more research is needed to establish evidence indicating when the replication of critical levels of local water overdraft may trigger large-scale impacts on Earth system processes (Lewis 2012), including collapsing terrestrial and aquatic ecosystems, major shifts in moisture feedback, and freshwater-ocean mixing. PB-Water can thus be of global significance if aggregated, but there is no global threshold as such. This bears difficulties in receiving its political message; if a safe space is based on single global number it will be treated accordingly. Currently, PB-Water suggests we can still expand human water use by one third, while critical tipping points are being reached regionally (e.g. fatal example of the Aral sea), which gives reason to critique (Nordhaus et al. 2012). On the other hand, a global number is important because it provides a clear benchmark and actionable policy target (Molina 2009), which explains the huge cross-sectoral influence of the planetary boundary concept.

The major challenge for research in this field over the course of the next decade will be to develop a mechanistic understanding of the interactions of environmental limits to eventually accumulate comprehensive knowledge about the coupled safe operating space for humanity. This is, viable solutions must not only respect each of the planetary boundaries, but also their interaction. Today, there is little knowledge on such dynamic couplings and a timely research agenda should include model-based representations of simultaneous planetary boundary processes. With respect to the work in this thesis, future directions would most importantly comprise interactions of freshwater use, land-system change (intimately linked with biosphere integrity), biochemical flows, and climate change, to establish a consistent framework for modeling a more sophisticated safe operating space and deploying therein pathways for human development. In the end, comprehensive integrated Earth system models require a social and economic domain, even though advancing (e.g. the Potsdam Integrated Assessment Model, not yet published), they are still in their infancy to this day.

6.3. Conclusions

6.3.1. Summary

The results of this thesis provide robust and spatially explicit evidence for the following key finings:

- **39% of renewable freshwater withdrawals for irrigation occur at the cost of environmental flows and are unsustainable**
- **Spatial patterns of environmental flows indicate that PB-Water might be notably lower (2800 km^3/yr) than previously estimated**
- **Safeguarding environmental flows worldwide, would cut irrigated food production by 14%, with a >10% kcal loss on half of all irrigated land**
- **25% of global irrigation withdrawals are consumed non-beneficially, defining the range of saving potentials**
- **Expanding irrigation by feasible reductions in non-beneficial consumption, would intensify global kcal production by 26%**
- **Optimizing precipitation water use is capable of producing additional 25% kcal on current rainfed land**
- **Integrated farm water management might halve the global food gap by 2050 (kcal +40%), while buffering adverse climate change and without additional land or water needs**

This thesis' findings build upon the development of a dynamic, high-resolution, and well validated modeling framework to better understand challenges, opportunities, and interactions of different water management pathways toward the vision of the SDG agenda, related to agriculture and water. It includes (1) the quantitative upscaling of EFRs to global coverage, (2) the mechanistic assessment of feedbacks from EFRs on food production, and (3) a comprehensive and systematic assessment of hitherto largely unquantified food production possibilities within the safe operating space for human freshwater use. The results reveal new insights in the substantial dependency of current irrigation practice on unsustainable water overdraft across river systems, and show a significant impact on agricultural productivity if policy goals to safeguard EFRs would be implemented. In turn, farm water management exhibits tremendous cross-scale biophysical opportunities. The improvement and thereby expansion of irrigation systems, combined with the optimized use of precipitation water through simple, long-known agro-ecological practices such as organic mulching and rainwater harvesting, provide effective and accessible measures to compensate for adverse impacts from EFRs and climate change. When implemented, such integrated farm water management interventions could sustainably intensify global food production to the degree sufficient to halve the global food gap for a growing world population by 2050. While the findings need to be complemented by finer-scale research, robust general results define a possible pathway toward sustainable intensification of agriculture, and provide a quantitative foundation for a more comprehensive discussion of intensification opportunities, associated challenges, and specific development targets.

6.3.2. Potential implications

Ultimately, it is a societal decision if to accept the risks of transgressing environmental limits (Griggs et al. 2014), but with the United Nations' agreement to the 2030 Agenda of Sustainable Development, all countries[3] are now bound to this bold vision. The transition of world agriculture in face of its twin-challenge — accomplishing future food production without undermining the integrity of the Earth's environmental systems — requires a paradigm shift, at the cost of resource re-allocations, but as a prerequisite for a stable and resilient Earth system that can support long-term human prosperity. But since the benefits and values of natural ecosystems are difficult to quantify, they are unlikely to be adequately provisioned, which results in a political asymmetry in the pursuit of these competing goals. In essence, the SDGs build on little quantitative evidence of how to scale up food security, attain sustainable farming, and reset current unsustainable water use broad-based, while the latter builds the cornerstone for protecting and restoring life-supporting ecosystems and thus cross-domain sustainability. Vaguely defined targets and indicators currently act as a barrier to action, much research is needed to improve its scientific scrutiny and to devise accessible and expedient pathways. In this light the quantitative and transparent framework developed in this thesis can directly evaluate tradeoffs and my results may inform the discussion two-fold: First, highlighted biophysical possibilities can stimulate a more adequate positioning of agricultural water intervention in the portfolio of global strategies toward sustainable intensification. Chapter 5 (Jägermeyr et al. 2016) has thus been cited as a new benchmark to consider the broader role of sustainable intensification targets in the global food system (MacDonald et al. 2016). Second, the

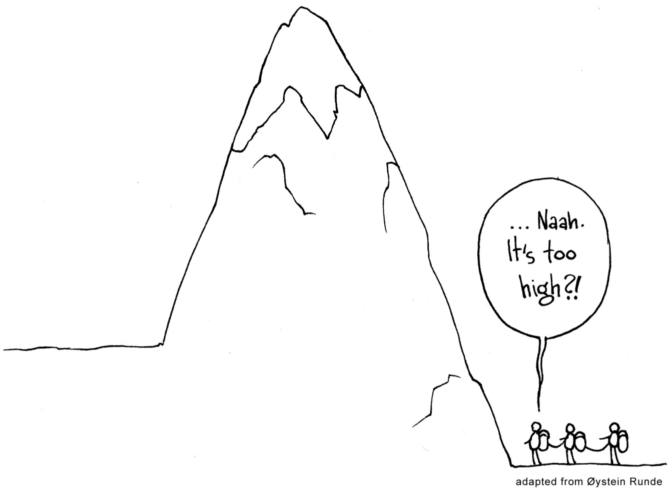
[3] There are 193 United Nations member states, including all undisputed independent states apart from Vatican City (United Nations 2016a).

findings quantitatively underpin SDG targets and their interdependencies, related to sustainable agriculture and water use. The published papers comprising this thesis provide global quantifications that can inform and catalyze further inquiry into local solutions and effective strategies facing complex burdens to implementation.

Water productivity improvements are imperative to realize sustainable intensification of agriculture to the scale required, but many global strategies in this context focus on improving soil fertility only (e.g. Chen et al. 2014). This thesis highlights that generating new water resources through improved water management in combined rainfed-irrigated systems — replacing traditionally separated views by a purely integrated solution portfolio — is a *sine qua non* for raising food production to the tremendous amount required. Being faced with the overall scale of opportunities in accessible on-farm farm water management for smallholder farmers, especially given the spectrum of positive externalities, they merit to be advocated with special emphasis to be mainstreamed among development strategies (Rockström and Falkenmark 2015; SEI 2005). In the end, water management is not a panacea, and integrates into an agro-ecological landscape approach, complemented by additional important merits that will further maximize synergies and global crop water productivity.

Closing statement

In view of humanity's historic achievements, this thesis opens with the quest for human ingenuity to tackle looming quandaries in the tightening water-food sphere. Certainly, new innovations will create superior breeds and new technologies will lift efficiencies to unprecedented levels. But when faced with the realm of untapped multifaceted opportunities accessible through already known practices, the twin-challenge of shifting agricultural systems onto environmentally sustainable grounds, while boosting underperforming systems, appears to be — in the first place — an implementation challenge. After all, it is clear that societies cannot grow indefinitely within environmental limits, but water resources are currently being used so inefficiently that there is evidently some room ahead of us for abundance within planetary boundaries.


... Naah.
It's too
high?!
adapted from Øystein Runde

Appendix

Appendix A.

Supplementary Information for Chapter 2

A.1. Water balance equations

Infiltration rates In for soil layer l:

$$In[l] = prec \times \sqrt{1 - \frac{w_a[l]}{W_{sat}[l] - W_{pwp}[l]}}, \tag{A.1}$$

where w_a is the actual available soil water content, W_{sat} and W_{pwp} are soil water content at saturation and wilting point, respectively, in mm. Soil water supply S is calculated as:

$$S = E_{max} \times w_r, \tag{A.2}$$

where E_{max} is the maximum transpiration rate in $mm\ d^{-1}$ (Gerten et al. 2004) and w_r is relative soil moisture available to roots. Atmospheric demand D is calculated as:

$$D = \frac{f \times PET \times pt}{1 + \frac{g_m}{g_{pot}}}, \tag{A.3}$$

where f is the fraction of the day with dry canopy (condition to transpire), PET is retrieved according to the Priestley-Taylor method and pt is the maximum Priestley-Taylor coefficient (1.391), g_m is a scaling coefficient (3.26 $mm\ s^{-1}$), and g_{pot} is the potential canopy conductance (Gerten et al. 2007).

A.2. Development of a new input for spatially explicit distribution of irrigation systems

The extent of irrigated areas (both equipped and actually irrigated) is relatively well documented and has been disaggregated to grid cell level by Stefan Siebert and Petra Döll et al. (Siebert et al. 2005; Siebert et al. 2007; Siebert et al. 2010; Siebert et al. 2015), which is included in the MIRCA2000 land use data set (Portmann et al. 2010) that we employ throughout our study (area equipped for irrigation). Information on the irrigation system that is in place is however less well documented. The FAO AQUASTAT data base (FAO 2014b) provides national irrigated areas separated for the three irrigation systems surface, sprinkler and drip (area equipped for irrigation). But such areas are not consistently available for all countries and significant gaps and errors are apparent. The International Commission on Irrigation and Drainage (ICID) also provides estimates on national shares of sprinkler and drip irrigated areas (ICID 2012), but unfortunately not for all countries. Rohwer et al. (2007) also compiled a country statistic on the share of irrigation systems, based on FAO, ICID and other sources but it is not comprehensive for all countries.

Here we compile a new country-level database on the extent of the three main irrigation systems surface, sprinkler and drip, based on FAO (2014b), ICID (2012), and Rohwer et al. (2007). In general, the total extent of actually irrigated areas is relatively consistent between MIRCA2000, AQUASTAT and ICID, but estimates of the extent of each system are often inconsistent or missing. We assume that the areas on which the three systems are implemented sum up to total area equipped for irrigation (i.e. that there are no other systems). Our primary data source is FAO (2014b) and in case of missing or inconsistent data we fill in with data from ICID (2012) or Rohwer et al. (2007). In countries where only the total irrigated area is available, we allocate shares according to neighboring countries. The complete list is shown in Table A.1.

Furthermore, we disaggregate country shares of each irrigation system to the irrigated area stated in MIRCA2000. Therefore, we developed and employed decision rules to decide which irrigation system is most suited for each CFT. Such decisions are based on Brouwer et al. (1988), Sauer et al. (2010), and Fischer et al. (2012) and are summarized in Table 2.2. The basic rationale is that drip irrigation is most suitable for high value crops, and sprinkler irrigation is suitable for most row, field, and tree crops (Brouwer et al. 1988). From the 12 CFTs in LPJmL we only excluded rice (always surface) and tropical roots (not irrigated at all) from this decision rule.

Our algorithm works in that first in each country all cells are selected that have areas with drip-suitable CFTs. From that pool, we randomly sample CFT fractions until the target area for drip systems is fulfilled in each country. This procedure is repeated 1000 times and we employ the iteration for which the target area is met most precisely. Then, sprinkler systems are attributed accordingly and the remaining free cell fraction for irrigation is assigned to surface irrigation. In the end, each CFT in each cell is assigned to one of the three irrigation systems.

The extent of irrigated areas by CFT changes each year (Siebert et al. 2015). Irrigation system distributions that were assigned for the previous year are kept in place for the next year, if the extent of irrigated cropland does not decline. On newly added cropland irrigation systems are distributed according to the rules above.

Table A.1.: Irrigation system shares by country. Country-level extent (in 1000 ha) and shares of surface, sprinkler, and drip irrigated areas, compiled from FAO (2014b), ICID (2012), and Rohwer et al. (2007).

Country	Equipped for surface irrigation	Equipped for sprinkler irrigation	Equipped for drip irrigation	Sum	Total area equipped (AQUASTAT)	Total area equipped (ICID)	Actually irrigated [%] (FAO)	Surface Share	Sprinkler Share	Drip Share	Notes
Afghanistan	3094.00	114.00	0.00	3208.00	3208.00		53.99	0.96	0.04	0.00	added 3094 to surf to meet FAO total area
Albania	397.00	0.03	0.00	397.03	188.40		56.53	1.00	0.00	0.00	added 473.4 to surf to meet FAO total area
Algeria	473.40	40.00	0.00	513.40	513.40		88.29	0.92	0.08	0.00	
Andorra	0.00	0.00	0.00	0.00	0.00			0.00	0.00	0.00	
Angola	85.53	0.00	0.00	85.53	85.53		13.47	1.00	0.00	0.00	
Antigua and Barbuda	0.00	0.03	0.10	0.13	0.13			0.02	0.19	0.79	added 85 to surf to meet FAO total area
Argentina	1949.00	281.00	127.00	2357.00	2357.00		91.73	0.83	0.12	0.05	
Armenia	247.50	25.00	1.00	273.50	273.50		64.35	0.91	0.09	0.00	
Australia	1831.00	524.00	191.00	2546.00	2546.00	2545.00		0.72	0.21	0.07	
Austria	0.00	115.00	2.00	117.00	117.00		37.13	0.00	0.98	0.02	added 115 to sprink to meet FAO total area
Azerbaijan	817.90	607.00	0.10	1425.00	1425.00	1433.00	95.30	0.57	0.43	0.00	
Bahamas, The	0.00	0.00	0.00	0.00	0.00		0.00	0.00	0.00	0.00	
Bahrain	3.39	0.16	0.47	4.01	4.01		100.00	0.84	0.04	0.12	
Bangladesh	5050.00	0.00	0.00	5050.00	5050.00		88.32	1.00	0.00	0.00	
Barbados				0.00	5.43			0.00	0.00	0.00	
Byelarus	0.00	131.00	0.00	131.00	115.00			0.00	1.00	0.00	
Belgium	0.00	23.35	0.00	23.35	23.35		24.33	0.00	1.00	0.00	added 23 to sprink to meet FAO total area
Belize	3.19	0.30	0.05	3.54	3.55		100.00	0.90	0.09	0.01	Shares based on neighboring countires
Benin	5.04	4.57	1.36	10.97	23.04		74.65	0.46	0.42	0.12	
Bhutan	27.68	0.00	0.00	27.68	31.91		100.00	1.00	0.00	0.00	
Bolivia	275.90	17.60	3.70	297.20	297.20		100.00	0.93	0.06	0.01	
Bosnia and Herzegovina	1.40	1.40	0.20	3.00	3.00			0.47	0.47	0.07	Shares based on neighboring countires
Botswana	0.22	0.89	0.27	1.38	1.44		100.00	0.16	0.65	0.20	
Brazil	2619.00	2446.00	334.80	5399.80	5400.00	4450.00	96.81	0.48	0.45	0.06	
Brunei	0.59	0.35	0.06	1.00	1.00		63.00	0.59	0.35	0.06	Based on Rohwer & Gerten 2007
Bulgaria	80.60	21.00	3.00	104.60	104.60	588.00	69.45	0.77	0.20	0.03	
Burkina Faso	25.39	3.90	0.44	29.73	29.73		85.00	0.85	0.13	0.01	

Burundi	6.96	0.00	0.00	6.96	6.96		64.08	1.00	0.00	0.00	
Cambodia	269.50	0.00	0.00	269.50	353.60		89.71	1.00	0.00	0.00	
Cameroon	17.02	5.43	0.00	22.45	22.45		100.00	0.76	0.24	0.00	
Canada	180.90	683.00	6.03	869.93	869.90	870.00	100.00	0.21	0.79	0.01	
Cape Verde	0.00	0.00	0.20	0.20	3.48		65.50	0.00	0.00	1.00	
Central African Republic	0.00	0.00	0.00	0.00	0.14		51.11	0.00	0.00	0.00	
Chad	26.52	3.75	0.00	30.27	30.27		86.55	0.88	0.12	0.00	
Chile	801.30	57.40	249.80	1108.50	1109.00	1090.00	98.65	0.72	0.05	0.23	
China	59338.00	2841.00	759.50	62938.50	62938.00	59300.00	86.15	0.94	0.04	0.01	
Colombia	856.80	36.90	6.30	900.00	1087.00		36.25	0.95	0.04	0.01	Based on Rohwer & Gerten 2007
Comoros	0.00	0.00	0.00	0.00	0.13		65.38	0.00	0.00	0.00	
Congo-Brazzaville	0.22	0.00	0.00	0.22	0.22		100.00	0.99	0.00	0.01	
Cook Islands	0.00	0.00	0.00	0.00	0.00			0.00	0.00	0.00	
Costa Rica	86.28	10.15	5.08	101.50	101.50		100.00	0.85	0.10	0.05	
Ivory Coast	11.75	36.00	0.00	47.75	47.75			0.25	0.75	0.00	
Croatia	1.84	1.67	0.12	3.63	3.63			0.51	0.46	0.03	
Cuba	366.60	402.70	19.49	788.79	788.80			0.47	0.51	0.03	
Cyprus	1.98	1.98	35.59	39.54	39.54			0.05	0.05	0.90	
Czech Republic	22.53	11.00	5.00	38.53	38.53	153.00	51.67	0.58	0.28	0.13	
North Korea	1460.00	0.00	0.00	1460.00	1460.00		92.53	1.00	0.00	0.00	
DR Congo, former Zaire	10.00	0.00	0.00	10.00	10.00			1.00	0.00	0.00	
Denmark	0.00	391.50	43.50	435.00	435.40		58.36	0.00	0.90	0.10	Based on Rohwer & Gerten 2007
Djibouti	0.00	0.00	0.00	0.00	1.01		38.34	0.00	0.00	0.00	
Dominica	0.00	0.00	0.00	0.00	0.00			0.00	0.00	0.00	
Dominican Republic	269.70	0.00	0.00	269.70	306.50		100.00	1.00	0.00	0.00	
Ecuador	663.90	170.10	19.40	853.40	1500.00		62.80	0.78	0.20	0.02	
Egypt	3029.00	171.90	221.40	3422.30	3422.00	3420.00	100.00	0.89	0.05	0.07	
El Salvador	41.56	2.49	1.18	45.22	45.23		74.82	0.92	0.06	0.03	
Equatorial Guinea	0.00	0.00	0.00	0.00	0.00			0.00	0.00	0.00	
Eritrea	4.10	0.00	0.00	4.10	4.10		100.00	1.00	0.00	0.00	
Estonia	0.00	3.68	0.00	3.68	0.46	1.00	71.18	0.00	1.00	0.00	
Ethiopia	283.20	6.36	0.01	289.57	289.60		100.00	0.98	0.02	0.00	
Faroe Islands	0.00	0.00	0.00	0.00	0.00			0.00	0.00	0.00	
Fiji	3.00	0.00	0.00	3.00	3.00			1.00	0.00	0.00	Shares based on neighboring countires
Finland	0.00	58.78	9.80	68.58	68.58	70.00	21.90	0.00	0.86	0.14	

France	1416.90	1379.80	103.30	2900.00	2642.00	2900.00	57.23	0.49	0.48	0.04	ICID 2012 and Rohwer & Gerten 2007
Gabon	1.57	1.57	0.00	3.15	3.15		100.00	0.50	0.50	0.00	Shares based on neighboring countires
Gambia, The	2.15	0.00	0.00	2.15	5.00		46.53	1.00	0.00	0.00	
Georgia	373.00	0.00	28.31	401.31	401.30		31.42	0.93	0.00	0.07	
Germany	10.70	500.00	5.00	515.70	515.70	540.00	45.49	0.02	0.97	0.01	
Ghana	24.60	6.30	0.00	30.90	30.90		90.32	0.80	0.20	0.00	
Greece	77.75	1088.50	388.75	1555.00	1555.00		82.32	0.05	0.70	0.25	Shares based on neighboring countires
Grenada	0.00	0.03	0.19	0.22	0.22			0.00	0.13	0.87	
Guatemala	198.60	94.43	19.08	312.11	337.50		100.00	0.64	0.30	0.06	
Guinea	19.93	0.30	0.16	20.39	20.39		100.00	0.98	0.01	0.01	
Guinea-Bissau	8.56	0.00	0.00	8.56	8.56		100.00	1.00	0.00	0.00	
Guyana	143.00	0.00	0.00	143.00	143.00		89.16	1.00	0.00	0.00	
Haiti	91.50	0.00	0.00	91.50	97.00		71.50	1.00	0.00	0.00	
Holy See	0.00	0.00	0.00	0.00	0.00			0.00	0.00	0.00	
Honduras	73.21	0.00	0.00	73.21	89.70		92.92	1.00	0.00	0.00	
Hungary	18.90	118.00	4.00	140.90	140.90	220.00	62.19	0.13	0.84	0.03	
Iceland	0.00	0.00	0.00	0.00	0.00			0.00	0.00	0.00	
India	61938.00	1446.00	578.20	63962.20	66334.00	60900.00	93.90	0.97	0.02	0.01	
Indonesia	6722.00	0.00	0.00	6722.00	6722.00		100.00	1.00	0.00	0.00	
Iran	7970.00	460.00	270.00	8700.00	8700.00	8700.00	77.41	0.92	0.05	0.03	Based on ICID 2012
Iraq	3402.33	96.59	26.09	3525.01	3525.00		54.89	0.96	0.03	0.01	Based on Rohwer & Gerten 2007
Ireland	0.00	0.50	0.60	1.10	1.10		100.00	0.00	0.46	0.55	Shares based on neighboring countires
Israel	0.00	60.00	168.80	228.80	225.00	231.00	80.67	0.00	0.26	0.74	
Italy	2399.00	981.20	570.60	3950.80	3951.00	2670.00	67.48	0.61	0.25	0.14	
Jamaica	19.04	4.41	1.76	25.22	25.22		100.00	0.76	0.17	0.07	
Japan	2010.00	430.00	60.00	2500.00	2500.00	2500.00	92.86	0.80	0.17	0.02	
Jordan	13.86	1.00	64.00	78.86	78.86		95.11	0.18	0.01	0.81	
Kazakhstan	713.00	1400.00	17.00	2130.00	1200.00	2130.00	98.50	0.34	0.66	0.01	Based on ICID 2012
Kenya	39.22	61.99	2.00	103.21	103.20		94.19	0.38	0.60	0.02	
Kiribati	0.00	0.00	0.00	0.00	0.00			0.00	0.00	0.00	
Kuwait	3.02	0.60	1.15	4.77	10.14		69.53	0.63	0.13	0.24	
Kyrgyzstan	1021.00	0.40	0.00	1021.40	1021.00		100.00	1.00	0.00	0.00	
Laos	155.40	0.00	0.00	155.40	310.00		87.32	1.00	0.00	0.00	
Latvia	0.00	0.00	0.00	0.00	0.83		74.70	0.00	0.00	0.00	
Lebanon	66.13	29.04	8.84	104.01	104.00		86.54	0.64	0.28	0.09	

Lesotho	1.32	1.00	0.32	2.64	2.64		2.54	0.50	0.38	0.12	Shares based on neighboring countires
Liberia	0.10	0.00	0.00	0.10	0.10		100.00	1.00	0.00	0.00	Shares based on neighboring countires
Libya	423.00	23.50	23.50	470.00	470.00		67.23	0.90	0.05	0.05	Shares based on neighboring countires
Liechtenstein	0.00	0.00	0.00	0.00	0.00			0.00	0.00	0.00	
Lithuania	0.00	9.25	0.00	9.25	1.34	4.40	74.63	0.00	1.00	0.00	
Luxembourg	0.00	1.00	0.00	1.00	0.00			0.00	1.00	0.00	
Madagascar	1084.00	2.40	0.00	1086.40	1086.00		50.64	1.00	0.00	0.00	
Malawi	6.36	43.19	5.45	55.00	73.50	55.00	98.18	0.12	0.79	0.10	
Malaysia	373.00	2.00	5.00	380.00	380.00	380.00	76.37	0.98	0.01	0.01	
Maldives	0.00	0.00	0.00	0.00	0.00			0.00	0.00	0.00	
Mali	166.90	0.03	0.14	167.07	167.10		83.72	1.00	0.00	0.00	
Malta	0.11	0.15	0.50	0.76	3.20		87.81	0.15	0.20	0.66	
Marshall Islands	0.00	0.00	0.00	0.00	0.00			0.00	0.00	0.00	
Mauritania	43.70	1.31	0.00	45.01	45.01		50.74	0.97	0.03	0.00	Shares based on neighboring countires
Mauritius	2.37	17.03	1.82	21.22	21.22		98.02	0.11	0.80	0.09	
Mexico	5168.00	310.80	143.10	5621.90	6460.00	6200.00	86.06	0.92	0.06	0.03	
Fed. St. of Micronesia	0.00	0.00	0.00	0.00	0.00			0.00	0.00	0.00	
Monaco	0.00	0.00	0.00	0.00	0.00			0.00	0.00	0.00	
Mongolia	13.90	43.40	0.00	57.30	57.30		61.08	0.24	0.76	0.00	
Montenegro	0.00	0.90	1.50	2.41	2.41		100.00	0.00	0.38	0.62	
Morocco	1209.00	151.70	97.97	1458.67	1459.00	1650.00	99.04	0.83	0.10	0.07	
Mozambique	131.04	156.00	24.96	312.00	118.10		33.92	0.42	0.50	0.08	Based on Rohwer & Gerten 2007
Myanmar (Burma)	2083.00	0.00	0.00	2083.00	2083.00		100.00	1.00	0.00	0.00	
Namibia	2.95	3.28	1.35	7.57	7.57		100.00	0.39	0.43	0.18	
Nauru	0.00	0.00	0.00	0.00	0.00			0.00	0.00	0.00	
Nepal	1134.00	0.00	0.00	1134.00	1168.00			1.00	0.00	0.00	
Netherlands	152.40	152.40	152.40	457.20	457.20		44.25	0.33	0.33	0.33	Based on Rohwer & Gerten 2007
New Zealand	110.90	491.40	41.66	643.96	619.30		82.19	0.17	0.76	0.07	
Nicaragua	61.37	0.00	0.10	61.47	199.10		72.38	1.00	0.00	0.00	
Niger	13.74	0.00	0.00	13.74	13.74		77.00	1.00	0.00	0.00	
Nigeria	238.10	0.05	0.00	238.15	238.20		91.86	1.00	0.00	0.00	
Niue				0.00				0.00	0.00	0.00	
Norway	61.35	0.01	0.00	61.36	114.90		47.84	1.00	0.00	0.00	
West Bank		12.00	12.00	24.00	24.00		100.10	0.00	0.50	0.50	Shares based on neighboring countires
Oman	46.66	6.65	5.54	58.85	58.85		100.00	0.79	0.11	0.09	

Pakistan	19270.00	0.00	0.00	19270.00	19270.00		100.00	1.00	0.00	0.00	
Palau				0.00				0.00	0.00	0.00	
Panama	23.90	3.74	4.50	32.14	32.14		100.00	0.74	0.12	0.14	
Papua New Guinea	45.73	14.77	1.05	61.55	62.55			0.74	0.24	0.02	Based on Rohwer & Gerten 2007
Paraguay	108.96	13.62	13.62	136.20	136.20		100.00	0.80	0.10	0.10	Shares based on neighboring countires
Peru	1697.00	21.74	10.63	1729.37	1729.00		64.14	0.98	0.01	0.01	
Philippines	1864.00	4.50	10.92	1879.42	1879.00	1520.00	100.00	0.99	0.00	0.01	
Poland	102.70	5.00	8.00	115.70	115.70	100.00	62.28	0.89	0.04	0.07	
Portugal	585.00	40.00	25.00	650.00	583.70	630.00	72.21	0.90	0.06	0.04	ICID 2012 and Rohwer & Gerten 2007
Puerto Rico	1460.00	95.38	23.84	1579.22	22.04		71.60	0.93	0.06	0.01	Based on Rohwer & Gerten 2007
Qatar	9.71	1.81	1.42	12.94	12.94		46.85	0.75	0.14	0.11	
South Korea	888.80	0.00	0.00	888.80	880.40	1010.00		1.00	0.00	0.00	
Moldova	68.00	145.00	15.00	228.00	228.30		72.12	0.30	0.64	0.07	
Romania	420.00	448.00	4.00	872.00	615.30	1500.00	28.18	0.48	0.51	0.01	
Russia	1953.00	2500.00	47.00	4500.00	2375.00	4500.00		0.43	0.56	0.01	Based on ICID 2012
Rwanda	3.50			3.50	4.62		43.24	1.00	0.00	0.00	
Saint Kitts and Nevis	0.00	0.00	0.02	0.02	0.02			0.00	0.00	1.00	
Saint Lucia				0.00	3.00			0.00	0.00	0.00	
St. Vincent & Grenadines				0.00				0.00	0.00	0.00	
American Samoa				0.00				0.00	0.00	0.00	
San Marino				0.00				0.00	0.00	0.00	
Sao Tome and Principe				0.00	9.70			0.00	0.00	0.00	
Saudi Arabia	706.00	716.00	198.00	1620.00	1620.00	1620.00	100.00	0.44	0.44	0.12	
Senegal	102.20		0.40	102.60	102.20		67.51	1.00	0.00	0.00	
Serbia	64.37	22.99	4.59	91.95	91.96		37.16	0.70	0.25	0.05	Shares based on neighboring countires
Seychelles	0.02	0.04	0.20	0.26	0.26		76.92	0.08	0.15	0.77	
Sierra Leone	1.00	0.00	0.00	1.00	1.00		100.00	1.00	0.00	0.00	
Singapore				0.00				0.00	0.00	0.00	
Slovakia	0.35	310.00	2.65	313.00	172.00	313.00	22.73	0.00	0.99	0.01	Based on ICID 2012
Slovenia	0.00	5.27	2.34	7.60	7.60	7.30	46.04	0.00	0.69	0.31	
Solomon Islands				0.00				0.00	0.00	0.00	
Somalia	50.00			50.00	50.00		100.00	1.00	0.00	0.00	
South Africa	385.00	920.00	365.00	1670.00	1670.00	1670.00	95.87	0.23	0.55	0.22	
South Sudan				0.00				0.00	0.00	0.00	
Spain	1029.00	783.00	1658.00	3470.00	3470.00	3470.00	89.14	0.30	0.23	0.48	

Sri Lanka	570.00	0.00	0.00	570.00	570.00		81.14	1.00	0.00	0.00	
Sudan	1758.00			1758.00	1758.00			1.00	0.00	0.00	
Suriname	50.32	1.10	0.00	51.42	57.00		100.00	0.98	0.02	0.00	
Swaziland	25.89	20.91	3.05	49.85	49.85		89.95	0.52	0.42	0.06	
Sweden	0.00	159.70	0.00	159.70	159.70		33.92	0.00	1.00	0.00	
Switzerland	0.83	59.17	1.00	61.00	61.00		59.31	0.01	0.97	0.02	Shares based on neighboring countires
Syria	1043.00	187.10	110.90	1341.00	1341.00	1280.00	95.50	0.78	0.14	0.08	
Tajikistan	742.10	0.00	0.00	742.10	742.10		90.88	1.00	0.00	0.00	
Thailand	6415.00			6415.00	6415.00		78.88	1.00	0.00	0.00	
Macedonia	49.00	5.00	1.00	55.00	127.80		62.32	0.89	0.09	0.02	Based on ICID 2012
Timor-Leste				0.00	34.65		83.43	0.00	0.00	0.00	
Togo	2.30	0.55	0.01	2.86	2.30		47.39	0.80	0.19	0.00	
Tokelau				0.00				0.00	0.00	0.00	
Tonga				0.00				0.00	0.00	0.00	
Trinidad and Tobago	2.89	0.71	0.12	3.71	3.60		85.00	0.78	0.19	0.03	
Tunisia	215.00	90.00	62.00	367.00	367.00		100.00	0.59	0.24	0.17	
Turkey	4690.00	500.00	150.00	5340.00	5340.00	5340.00	84.63	0.88	0.09	0.03	
Turkmenistan	1991.00	0.00	0.00	1991.00	1991.00		100.00	1.00	0.00	0.00	
Tuvalu				0.00				0.00	0.00	0.00	
Uganda	5.35	0.23		5.58	12.08		100.00	0.96	0.04	0.00	
Ukraine	525.00	2080.00	0.00	2605.00	2175.00	2180.00		0.20	0.80	0.00	
United Arab Emirates	27.10	4.00	195.50	226.60	92.00		82.61	0.12	0.02	0.86	
United Kingdom	117.00	105.00	6.00	228.00	228.00	110.00	60.61	0.51	0.46	0.03	
Tanzania, United Republic of	184.30			184.30	184.30		100.00	1.00	0.00	0.00	
United States	12696.00	12333.00	1615.00	26644.00	26644.00	24700.00	85.97	0.48	0.46	0.06	
Uruguay	200.00	18.00	20.00	238.00	238.00		100.00	0.84	0.08	0.08	
Uzbekistan	4276.00	0.00	4.51	4280.51	4198.00	4233.00	88.14	1.00	0.00	0.00	
Vanuatu				0.00				0.00	0.00	0.00	
Venezuela	735.50	275.50	44.30	1055.30	1055.00		92.78	0.70	0.26	0.04	
Vietnam	4584.00	1.10	0.00	4585.10	4585.00		100.00	1.00	0.00	0.00	
Yemen	453.80	0.35	0.48	454.63	454.30		100.00	1.00	0.00	0.00	
Zambia	32.19	17.57	5.63	55.39	55.39		100.00	0.58	0.32	0.10	
Zimbabwe	46.85	112.80	13.88	173.53	173.50		71.41	0.27	0.65	0.08	

A.3. Supplementary figures

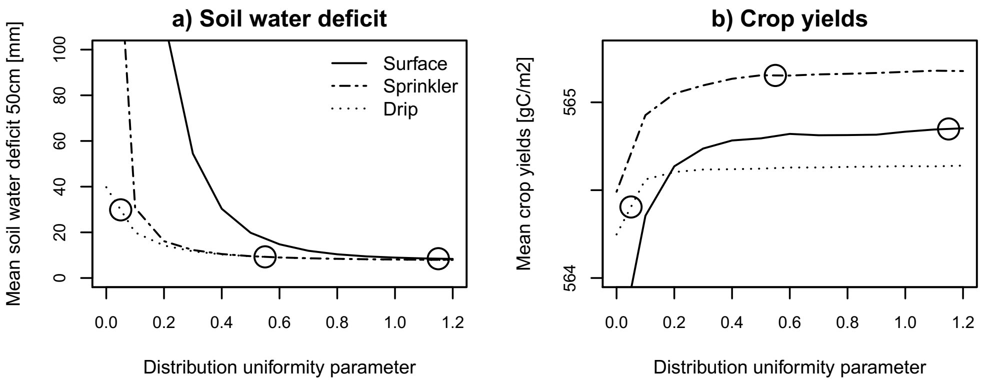


Figure A.1.: Parameter sensitivity analysis for the distribution uniformity scalar. Panel **(a)** shows the dependency of the distribution uniformity scalar (du) on annually cumulated soil water deficit in the upper 50 cm (irrigation depth) that could not be fulfilled by irrigation, as mean over irrigated cells. Panel **(b)** shows the dependency on mean annual crop yield. Simulations are based on All-Surf, All-Sprinkler, and All-Drip scenarios (see Section 2.3.5) assuming unrestricted water availability for irrigation. Employed parameter estimates are indicated. Surface and sprinkler systems are parameterized to meet net irrigation requirement (field capacity in upper 50 cm) and thus yield production is at its potential. Drip systems are parameterized to represent a modest form of deficit irrigation, not to maximize yields but to save water.

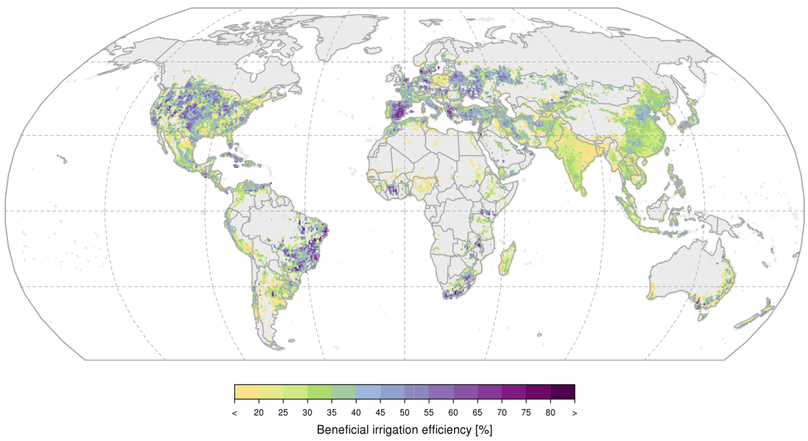


Figure A.2.: Global patterns of beneficial irrigation efficiency(E_b). E_b is the ratio of transpired and diverted, here shown as area-weighted mean over CFTs (**inclusive** "others" and pastures) and based on the system distribution in Figure 2.3. Gridded data for this figure are provided as Supplement for other studies.

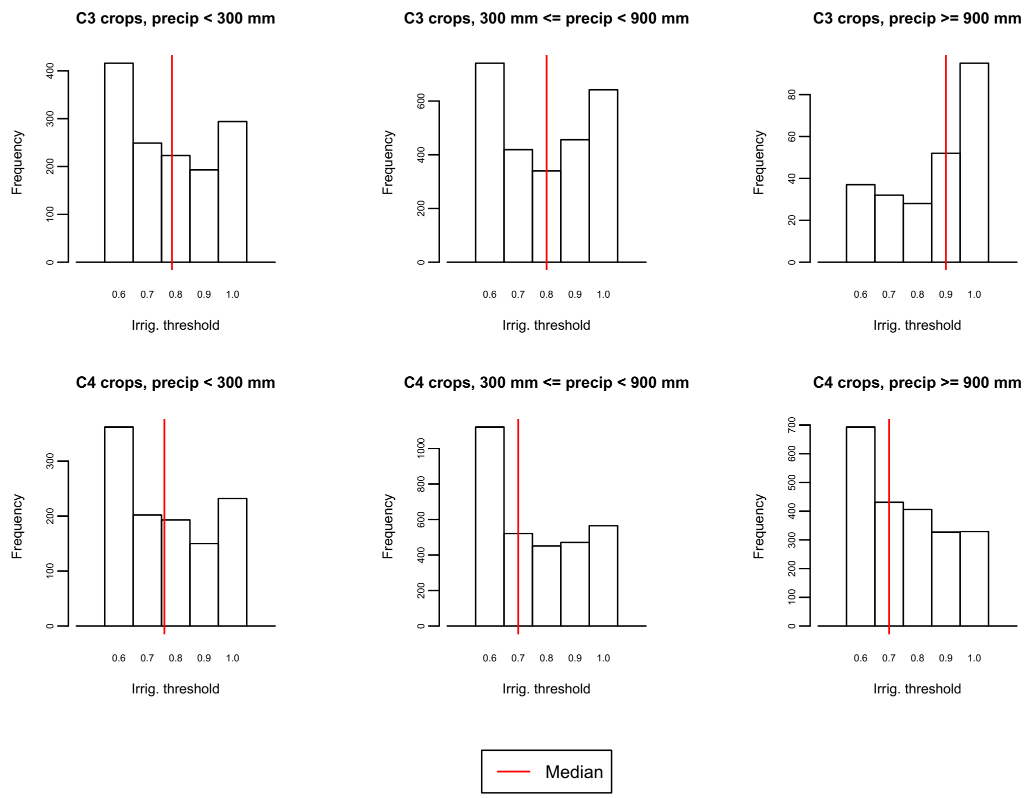


Figure A.3.: Sensitivity analysis for the irrigation threshold parameter. Stacks represent the number of cells that achieve their maximum harvest at the respective irrigation threshold (*it*) and the red line is the median across all cells. The two rows represent C3 and C4 crops, respectively, and the columns represent the indicated precipitation regimes.

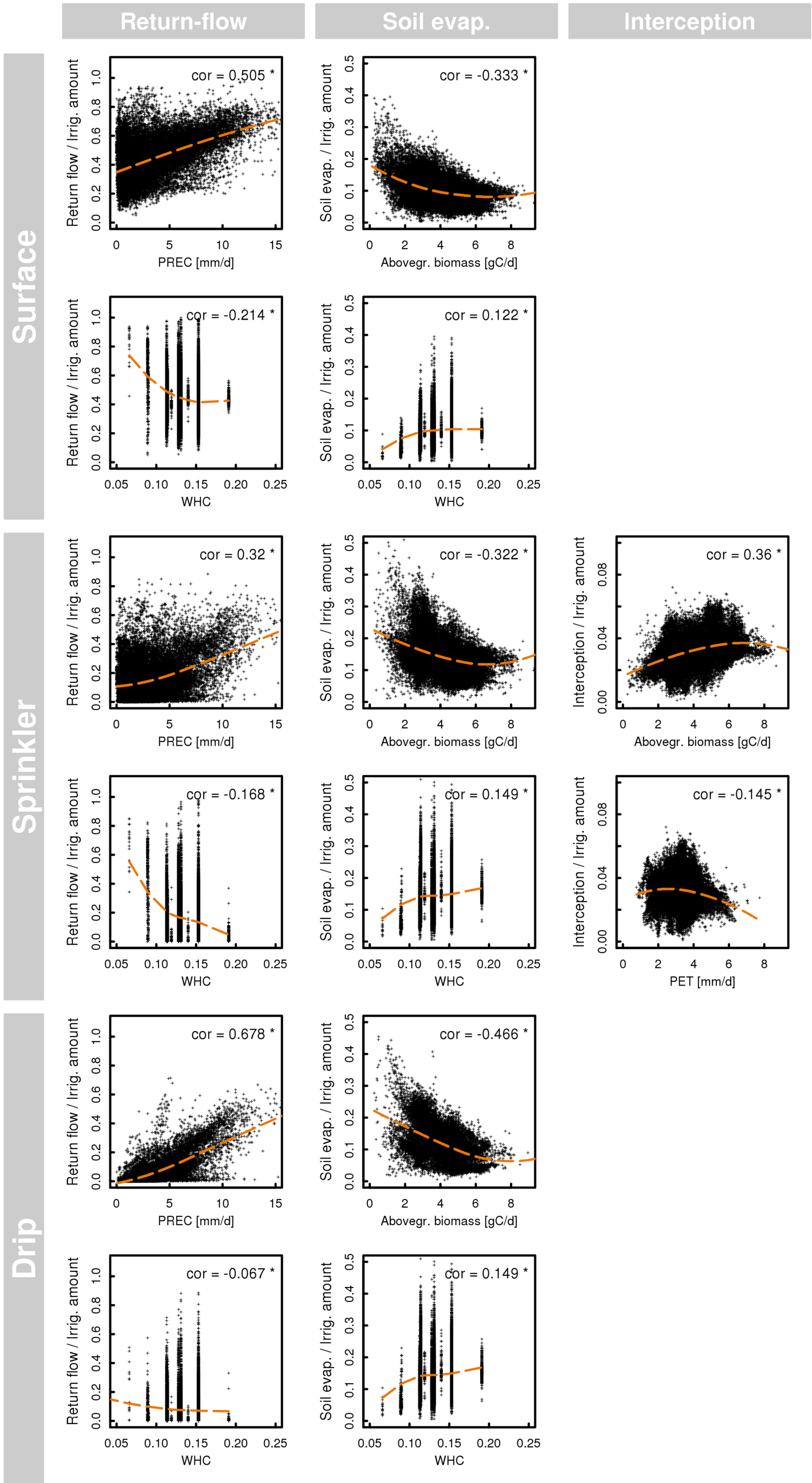


Figure A.4.: Dependencies of non-beneficial irrigation water fluxes on its main biophysical driving factors. The three columns represent return flow, soil evaporation, and interception, double rows represent the irrigation system: surface, sprinkler, and drip. Data are based on 12 crop CFTs from the All-Surface, All-Sprinkler and All-Drip scenario, respectively and country-scale management intensities are harmonized (calibration factors are set so as to represent systems with optimal management). Dashed lines indicate polynomial bias curve, “cor” refers to Spearman’s correlation coefficient (*, if p-value $< 10^{-9}$). PREC: precipitation, WHC: water holding capacity, PET: potential evapotranspiration.

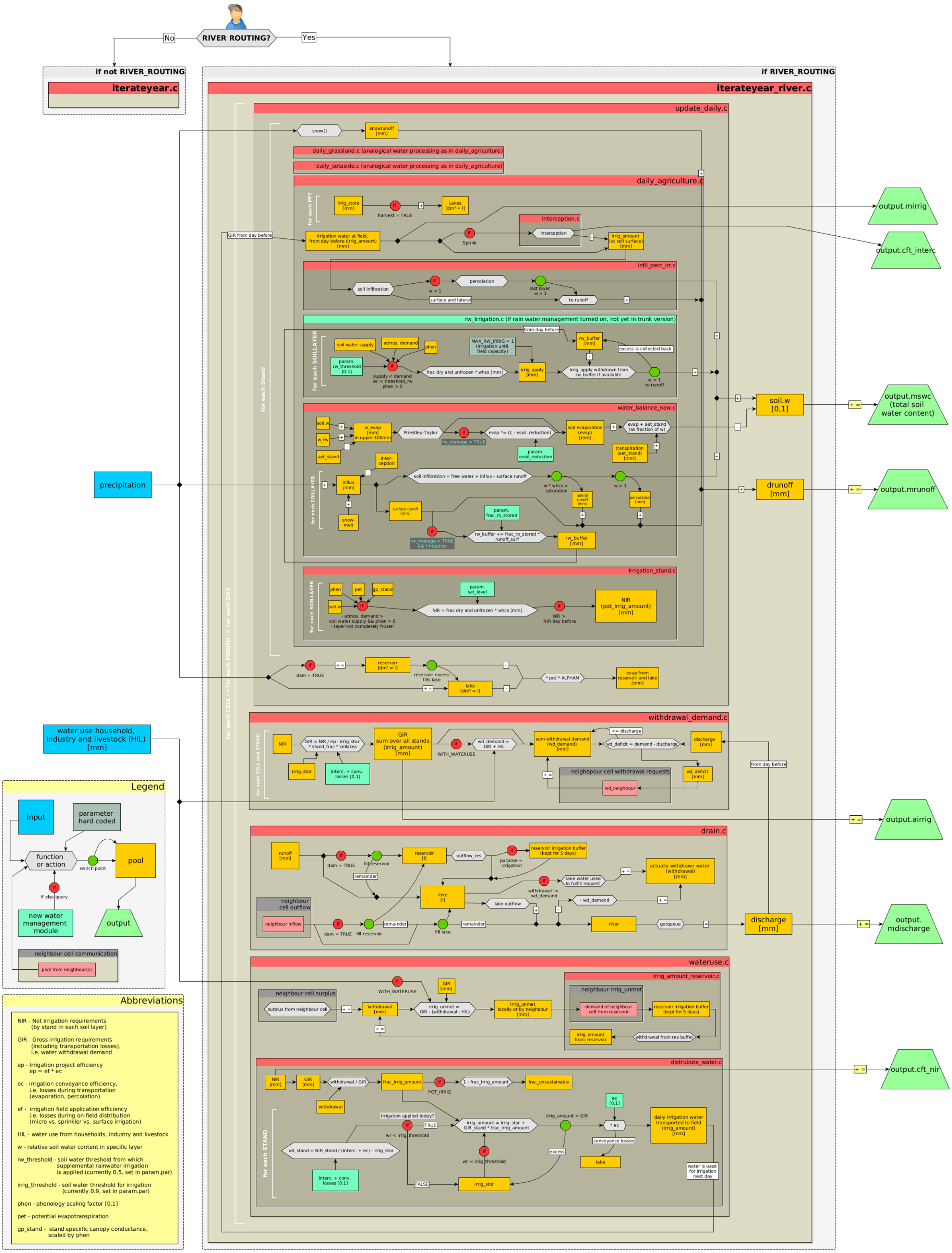


Figure A.5.: LPJmL river routing. This diagram illustrates a simplification of the water balance and river routing module in LPJmL.

Appendix B.

Supplementary Information for Chapter 4

B.1. Supplementary tables and figures

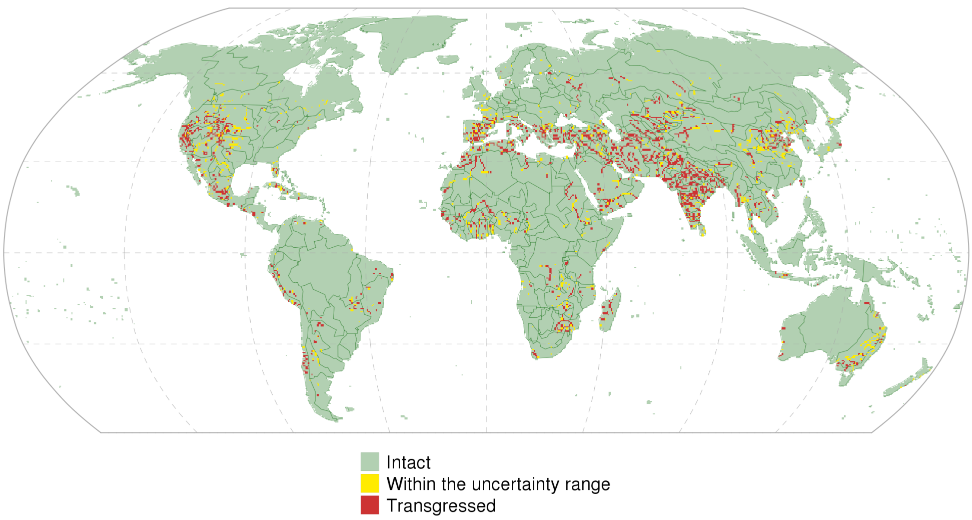


Figure B.1.: Uncertainty range of the current status of environmental flow transgressions. The degree to which EFRs are tapped is expressed as the transgression-to-uncertainty ratio (>5% "within uncertainty range", >100% "beyond uncertainty range", see Methods), averaged over months with EFR transgressions (1980–2009, 0.5° resolution). Borders delineate Food Production Units. See Figure B.1 for total annual EFR deficits together with the number of months with EFR transgressions.

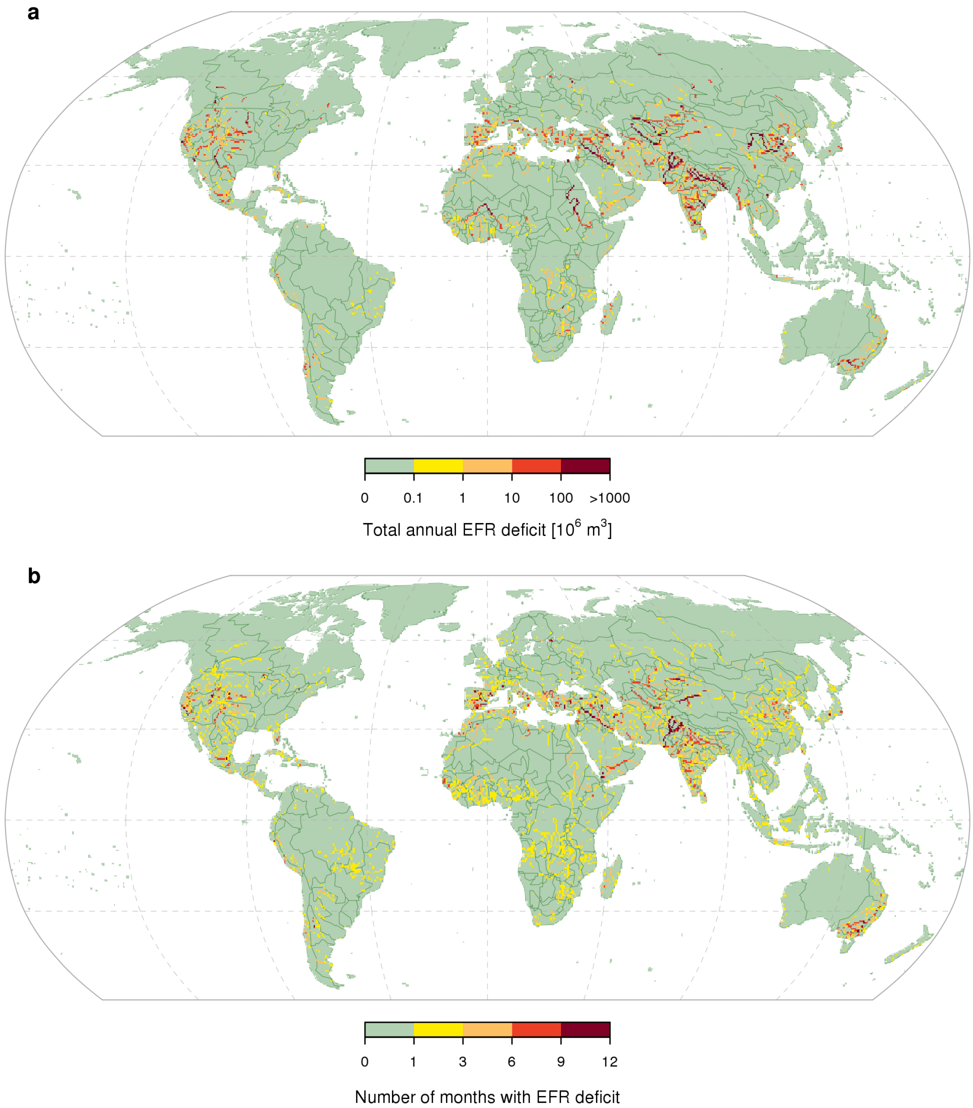


Figure B.2.: Current status of environmental flow transgressions in absolute terms. Map (**a**) illustrates the total annual EFR transgressions in million m^3 (mean of three EFR methods), map (**b**) shows the number of months per year in which at least one of the three EFR methods indicates an EFR transgression $> 0.1\ m^3/s$ (1980–2009, 0.5° resolution).

Table B.1.: Global sums of food production and water abstractions for different management scenarios. Global sums of kcal production, area affected (kcal loss > 10%), irrigation water withdrawal (IWD) and consumption (IWC), and withdrawal and consumption for household, industry, and livestock (HIL_{WD} and HIL_{WC}) are shown for the following scenarios: current situation (0., for consistency with Table 1, counting starts with 0.), in the absence of irrigation (1.), with irrigation constrained by EFRs (2., for 3 methods respectively), and with upgraded irrigation constrained by EFRs (3., for 3 methods respectively), details in Methods. The simulation period is 1980–2009.

	Total production $[10^{13} kcal]$	Irrigated production $[10^{13} kcal]$	Total area affected $[Mha]$	Irrig. area affected $[Mha]$	IWD $[km^3]$	IWC $[km^3]$	HIL_{WD} $[km^3]$	HIL_{WC} $[km^3]$
0. Today	740.0	244.2	0.0	0.0	2409.3	1254.7	1070.5	192.8
1. No irrigation	631.6	135.8	262.1	157.2	0.0	0.0	1,090.8	196.5
2. Respect EFR								
Tessmann$_{adapted}$	700.8	205.0	145.7	108.7	1305.5	756.8	802.5	143.6
VMF	712.6	216.7	116.2	93.3	1570.1	891.9	909.4	163.3
Smakhtin$_{adapted}$	704.7	208.8	128.8	102.2	1361.3	794.1	790.2	141.6
3. Respect EFR with irrigation upgrade								
Tessmann$_{adapted}$	732.9	251.7	117.5	81.2	1017.0	761.3	797.7	142.4
VMF	746.9	265.7	79.8	53.2	1214.7	889.7	904.2	162.0
Smakhtin$_{adapted}$	737.7	256.4	92.2	62.0	1065.0	801.6	784.8	140.1
4. Respect EFR with integrated water management								
Tessmann$_{adapted}$	807.3	254.5	84.4	74.9	986.7	737.5	792.5	141.8
VMF	821.2	268.4	53.7	46.9	1183.5	864.8	902.3	161.9
Smakhtin$_{adapted}$	812.1	259.3	60.8	55.0	1034.6	777.4	777.6	139.4

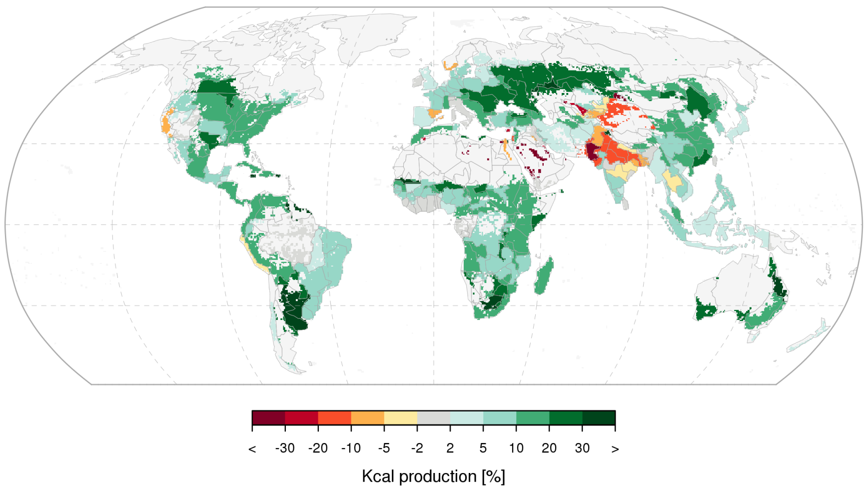


Figure B.3.: Integrated water management overcompensates EFR effects on kcal production globally. The change in total kcal production under integrated water management (scenario 4 in Table B.1), yet constrained by EFRs, with respect to the current situation and aggregated to Food Production Units (1980-2009). Regions with marginal change are shaded (dark grey) and cells without significant cropland fraction (<0.1%) are masked (light grey).

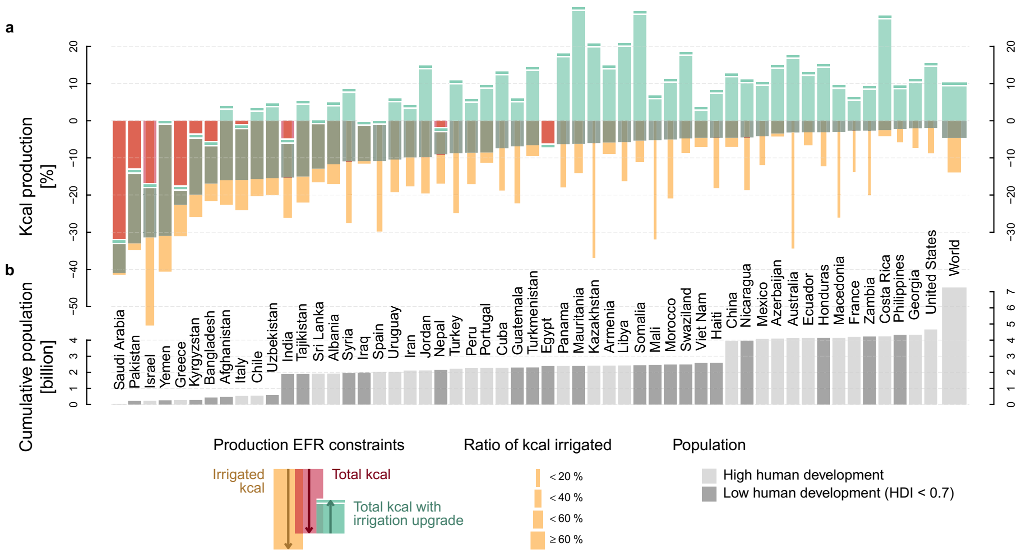


Figure B.4.: EFR constraints on country-level kcal production under integrated water management. Same caption as for Figure 4.3 applies, but for integrated water management (scenario 4 in Table B.1).

Table B.2.: Country-level aggregation of changes in kcal production under EFR constraints and irrigation improvements. Numbers in this table are illustrated in Figure 3. "Irrigated kcal" and "Total kcal" refer to the change from scenario 0 to 2, respectively. "Total kcal, managed" shows the change between scenario 0 and 3. "Irrigated cropland" refers to scenario 2, "Irrigated cropland expanded" to scenario 3. The "Ratio of kcal irrigated", i.e. irrigated production to total production is calculated with scenario 0. Population data are derived from United Nations (2015c) and the Human development Index (HDI) from UNDP (2015). Countries with <0.01 Mha irrigated cropland or <1 million population are omitted.

	Irrigated kcal [% change]	Total kcal [% change]	Total kcal, irrigation upgrade [% change]	Irrigated cropland [Mha]	Irrigated cropland expanded [Mha]	Ratio of kcal irrigated [%]	Population 2015 [$million$]	HDI [0,1]
Saudi Arabia	-41.43	-41.03	-33.45	0.33	0.37	99	32	0.84
Pakistan	-34.80	-33.01	-17.16	10.37	11.41	95	194	0.54
Israel	-55.10	-31.40	-30.84	0.02	0.02	57	8	0.89
Yemen	-40.59	-30.94	-21.68	0.32	0.39	76	28	0.50
Greece	-31.10	-22.60	-21.50	0.38	0.40	73	11	0.86
Kyrgyzstan	-25.88	-19.90	-10.21	0.31	0.34	77	6	0.66
Bangladesh	-21.61	-16.91	-7.60	4.46	5.31	78	159	0.57
Afghanistan	-22.60	-16.03	-4.13	1.38	1.66	71	36	0.46
Italy	-24.09	-15.94	-8.05	1.62	1.96	66	61	0.87
Chile	-20.30	-15.71	-3.13	0.39	0.47	77	18	0.83
Uzbekistan	-19.98	-15.48	-1.13	1.00	1.20	77	30	0.68
India	-26.10	-15.29	-10.57	52.59	62.32	59	1307	0.61
Tajikistan	-22.01	-15.02	0.36	0.16	0.19	68	7	0.62
Sri Lanka	-16.58	-12.89	-4.22	0.43	0.50	78	22	0.76
Albania	-17.01	-11.73	-2.65	0.14	0.16	69	3	0.73
Syria	-27.56	-10.95	-6.96	0.77	0.82	40	23	0.59
Iraq	-11.55	-10.85	-2.12	1.75	1.88	94	36	0.65
Spain	-29.82	-10.83	-9.23	1.21	1.35	36	47	0.88
Uruguay	-19.29	-10.45	-2.50	0.18	0.21	54	3	0.79
Iran	-17.66	-9.88	-3.85	3.93	4.42	56	79	0.77
Jordan	-19.57	-9.75	-6.66	0.01	0.01	50	7	0.75
Nepal	-16.92	-9.05	-4.57	1.07	1.31	53	33	0.55
Turkey	-24.88	-8.75	-4.52	2.52	2.96	35	77	0.76
Peru	-17.05	-8.61	3.02	0.60	0.80	50	31	0.73
Portugal	-11.31	-8.56	5.14	0.26	0.32	76	11	0.83
Cuba	-18.79	-7.41	-1.71	0.56	0.70	39	11	0.77
Guatemala	-22.24	-6.90	0.26	0.11	0.14	31	17	0.63
Turkmenistan	-9.44	-6.59	8.37	0.48	0.58	70	5	0.69
Egypt	-6.50	-6.50	-6.91	1.52	1.55	100	88	0.69
Panama	-17.94	-6.31	12.51	0.03	0.05	35	4	0.78
Mauritania	-14.10	-6.20	16.76	0.01	0.02	44	4	0.51
Kazakhstan	-36.91	-6.00	-4.12	0.65	0.74	16	17	0.79
Armenia	-8.91	-5.86	6.03	0.11	0.13	66	3	0.73
Libya	-16.30	-5.74	-2.87	0.08	0.09	35	7	0.72
Somalia	-11.06	-5.35	12.93	0.10	0.15	48	11	0.35
Mali	-31.94	-5.23	-0.86	0.18	0.25	16	18	0.42
Morocco	-20.92	-5.05	-2.11	0.73	0.84	24	34	0.63
Swaziland	-8.54	-4.76	11.82	0.03	0.04	56	1	0.53
Viet Nam	-7.04	-4.58	2.23	3.18	3.80	65	94	0.67
Haiti	-18.16	-4.58	3.00	0.10	0.15	25	11	0.48
China	-7.01	-4.58	6.88	50.67	63.19	65	1367	0.73
Nicaragua	-18.69	-4.50	5.10	0.07	0.10	24	6	0.63
Mexico	-11.92	-4.15	4.45	3.82	5.06	35	120	0.76
Azerbaijan	-4.25	-3.45	9.67	0.63	0.73	81	10	0.75

Australia	-34.38	-3.17	-2.14	0.56	0.68	9	24	0.94
Ecuador	-6.62	-3.13	11.32	0.42	0.57	47	16	0.73
Honduras	-12.27	-3.11	6.10	0.05	0.07	25	8	0.61
Macedonia	-26.07	-2.99	-2.68	0.02	0.02	11	2	0.75
France	-13.77	-2.68	-0.91	1.90	2.37	19	64	0.89
Zambia	-20.09	-2.67	-1.41	0.04	0.04	13	15	0.59
Costa Rica	-4.16	-2.50	24.19	0.05	0.08	60	5	0.77
Philippines	-5.79	-2.18	6.14	1.37	1.81	38	101	0.67
Georgia	-7.22	-2.04	0.26	0.09	0.10	28	4	0.75
United States	-8.69	-1.94	1.27	13.84	16.69	22	322	0.92
World	-13.93	-4.59	-0.11	193.40	234.35	33	7269	0.71

B.2. Methods

B.2.1. Environmental flow requirement objectives

We estimate EFRs, irrigation demand and withdrawals, and crop calorie production with a biosphere model that simulates these processes daily, as an intrinsic part of natural and managed ecosystem dynamics. We use the concept of EFRs to allocate maximum allowed monthly water withdrawals, expressed as a percentage of “pristine” undisturbed mean monthly river flow (determined globally for each 0.5° grid cell from a simulation without considering human land use, water infrastructure, and water withdrawals; forced with climate data of the simulation period 1980–2009; see below). We include three hydrological EFR estimation methods to depict an uncertainty range, which reflects methodological differences and which can be interpreted as the outcome of different environmental policies. Based on a simulation considering current agricultural patterns, reservoir management, and multi-sectoral human water withdrawals (see Model and simulation protocol below), this uncertainty range is also used to classify river segments according to the current status of transgression of EFRs, i.e. the sub-global freshwater use boundary (Steffen et al. 2015) (Figure B.1).

The EFR calculation methods aim at reaching a “fair” ecological status, which is a conservative assumption as this status can still be characterised by disturbed biota, loss or reduction in spatial distribution of sensitive species, and occurrence of alien species (Smakhtin et al. 2004). The Tessmann (1980) method and the “Variable Monthly Flow” method (Pastor et al. 2014) account for seasonal EFR variation by distinguishing high-, intermediate-, and low-flow regimes based on different proportions of mean monthly river flow (MF) and mean annual flow (AF) of long-term average “pristine” conditions (Table B.3). To protect habitat maintenance and essential flow variability,

Table B.3.: Definition of hydrological seasons and respective EFR allocations. Mean monthly flow (MF), mean annual flow (AF) refer to pristine river flows, Q_{90} (Q_{50}) defines the base flow that is on average exceeded 90% (50%) of the time (simulated under 1980-2009 climate but in the absence of human water flow and land-use alterations). The Variable Monthly Flow method (VMF) is used following its original formulation (Pastor et al. 2014), and modified versions of the Tessmann and Smakhtin et al. methods are used as described in the Methods section.

EFR method	**F**low regime classification		**E**nvironmental flow requirements		
	low-flow	high-flow	low-flow	intermediate-flow	high-flow
Tessmann$_{adapted}$	MF $\leq$ 40% AF	MF > AF	80% MF	40% AF	40% MF
VMF	MF $\leq$ 40% AF	MF > 80% AF	60% MF	45% MF	30% MF
Smakhtin$_{adapted}$	MF $\leq$ 80% AF	MF > 80% AF	$Q_{90} + h$	-	$Q_{50} + h$
			$h = \begin{cases} 0, & \text{if } Q_{90} > 30\% AF \\ 7\% AF, & \text{if } Q_{90} \leq 30\% AF \\ 15\% AF, & \text{if } Q_{90} \leq 20\% AF \\ 20\% AF, & \text{if } Q_{90} \leq 10\% AF \end{cases}$		

supporting the "natural flow paradigm" (Richter et al. 2012), for each month different flow volumes are allocated to EFRs based on the flow regime (Table B.3). In this study we use an adapted version of Tessmann's method and replace the most restrictive parameter that allocates 100% of river flow during low flow periods by more realistic 80%, a value proposed by Richter et al. (2012) and also employed in other studies (e.g Hoekstra et al. 2011).

The Smakhtin et al. (Smakhtin et al. 2004) method assumes static EFRs throughout the year, but comprises two components, a minimum baseflow (exceeded 90% of the time, Q_{90}) and a percentage of AF depending on mean seasonal river flow variability. For rivers with stable seasonal flow and thus high Q_{90} values relative to AF (Q_{90} > 30% AF), only the baseflow is allocated. In case of higher flow variability (Q_{90} can go down to zero for intermittent rivers), fractions of AF are allocated additionally (Table B.3). As the Smakhtin et al. method provides by definition a seasonally constant EFR target, which has been criticized (Arthington et al. 2006; Richter et al. 2012), we adapt Smakhtin et al.'s Q_{90} method to allow for seasonal variation in that we allocate Q_{50} during high flow periods (see Table B.3), as proposed by Pastor et al. (2014). In addition, we restrict EFR allocations to not exceed 80% of monthly pristine river flow.

Overall, such conceptually simple "per cent of flow" approaches are commonly used proxies for EFR estimates, because they are applicable at large scales and can provide a high degree of protection for natural flow variability when implemented (Richter et al. 2012).

B.2.2. Illustration of pressure on the freshwater boundary.

The status of the freshwater boundary displayed in Figure B.1 is based on the proportion of EFR deficit (EFR_{def}) and the EFR uncertainty (range of EFR estimates from three methods as defined above), calculated for each month and grid cell (EFR_{status}). EFR_{status} is shown as the average over months in which both pristine river discharge and current EFR_{def} are $\geq 0.1\ m^3/s$, throughout the simulation period 1980–2009. $EFR_{def} = max(EFR - current\ discharge, 0)$ is calculated as the mean of the three EFR methods. The map in Figure 4.2a illustrates the proportion of mean annual EFR_{def} and current mean annual discharge. See Figure B.2a for the sum of annual EFR_{def} in million m^3, and Figure B.2b for the average number of months in which at least one of three methods indicates $EFR_{def} \geq 0.1\ m^3/s$.

B.2.3. Model and simulation protocol

The LPJmL model globally represents biogeochemical land surface processes, simulating daily water fluxes in direct coupling with the establishment, growth, and productivity of major natural and agricultural plant types at 0.5° resolution. Crop production is represented by 12 specified crop functional types, irrigated or rainfed. Spatially explicit data on cropland extent and the mechanistic representation of irrigation systems is described in Jägermeyr et al. (2015). Carbon assimilated through photosynthesis is allocated to harvestable storage organs (e.g. cereal grain) and three other pools (roots, leafs, stems). Sowing dates are calculated based on climate and crop type, but fixed during the simulation period after 1980. In tropical regions that exhibit predominant precipitation seasonality, sowing dates on irrigated land are forced to occur in the dry season. Land use patterns are held constant at year 2005. For all simulations, LPJmL is forced with the climate input data and spin-up protocol as described in Jägermeyr et al. (2016) for the time period 1980–2009.

A simulation omitting human water use is performed based on the same land use patterns, but under rainfed conditions only. Otherwise water demand for irrigation (internal mechanistic calculation) and for household, industry and livestock (external source accounting for both withdrawal and consumption (Flörke et al. 2013)) are constrained by local availability of renewable freshwater, including a representation of dams and reservoirs (Biemans et al. 2011) (with daily EFR release regime, yet channel and habitat maintenance floods not considered). Precipitation and irrigation water is partitioned into plant transpiration, soil evaporation, interception loss, surface and subsurface runoff, and deep percolation, in direct coupling to daily weather conditions and the surface, soil water, and energy balance (Jägermeyr et al. 2015). Surface and subsurface runoff are accumulated along the river network and subsequently available for downstream reuse. In this study there is no implicit assumption about contributions from fossil groundwater and water diversions, which are expected to amount to ∼20% of global irrigation water requirements (Wada et al. 2012). Based on these well-validated streamflow estimates (Figure 4.4), EFRs are calculated as described above. In the "respect EFR" simulation, total water withdrawal is temporally restricted as long as it would tap EFRs. For each above-defined EFR method we perform an individual model run, but results presented throughout the text refer to the mean of the three simulations and the standard deviation is assigned in Table 4.1 (individual results are shown in Table B.1).

Additionally we simulate a scenario of moderate irrigation system upgrade in which surface irrigation systems are assumed to be replaced by sprinkler systems (except paddy rice) and half of saved consumptive "losses" are assumed to be made available to expand irrigation into neighbouring rainfed cropland (total cropland area remains constant) (Jägermeyr et al. 2016). Since observed efficiency improvements do not necessarily result in lower water withdrawals (farmers often expand irrigation or use higher value crops, instead of losing water allocations) (Ward and Pulido-Velazquez 2008), we allocate half of saved consumptive water to irrigation expansion (if rainfed cropland is available in the same grid cell). Note that return flows are not considered savable losses throughout this study as they might be accessible for downstream users.

B.2.4. Model validation

The validation of LPJmL-simulated key variables for the time period 1980 to 2009 is highlighted in Figure 4.4. Uncalibrated LPJmL mean annual discharge simulations are compared with the latest observations from GRDC (Global Runoff Data Centre) stations (GRDC 2016). Global hydrological EFR estimations from this study are validated against local estimates comprising a wide variety of methods, including comprehensive holistic approaches. The comparison at 11 ecologically, hydrologically, and climatically different cases studies (details in Pastor et al. (2014)), reveals a fair agreement suggesting they capture a sufficiently broad range of environmental settings if applied to the global scale. Average country-level crop yield simulations exhibit high agreement with observations obtained from FAOSTAT (FAO 2012). The coefficient of determination (R^2) across top 30 producer countries ranges between 85 and 97% for the four major staple crops (wheat, rice, maize, and soy). In absolute terms, simulated global kcal production of $7.8 * 10^{15}$ kcal in year

2006 is ∼18% short of reported values ($9.5 * 10^{15}$ kcal (Alexandratos and Bruinsma 2012)), mostly because LPJmL currently does not account for multi-cropping systems.

Default LPJmL simulations show the capacity to explain a high fraction of observed inter-annual yield variability among the important producer countries (Figure B.5). In contrast, a potential full-irrigation simulation, in which irrigated as well as rainfed cropland is supplied with the optimal crop water demand throughout the growing season — i.e. water stress effects on crop growth are circumvented — shows the amount of explained variability to drop sharply and to turn statistically insignificant ($p \geq 0.1$). This effect appears especially pronounced for wheat (Figure B.5a–c), somewhat less distinct for maize (Figure B.5d–f) and disappears for rice (Figure B.5g–i). This can be explained by the fact that maize as a C4 crop is generally less sensitive to drought stress using a more efficient enzyme on the pathway of CO_2 fixation (Amthor 1995), while rice (mostly paddy rice) is assumed to be provided with sufficient soil water among the selected countries. This sensitivity analysis provides strong evidence for LPJmL's capability of representing observed water stress signals in crop growth, which is key to explaining inter-annual yield variability and thus feedbacks from water management on food production levels.

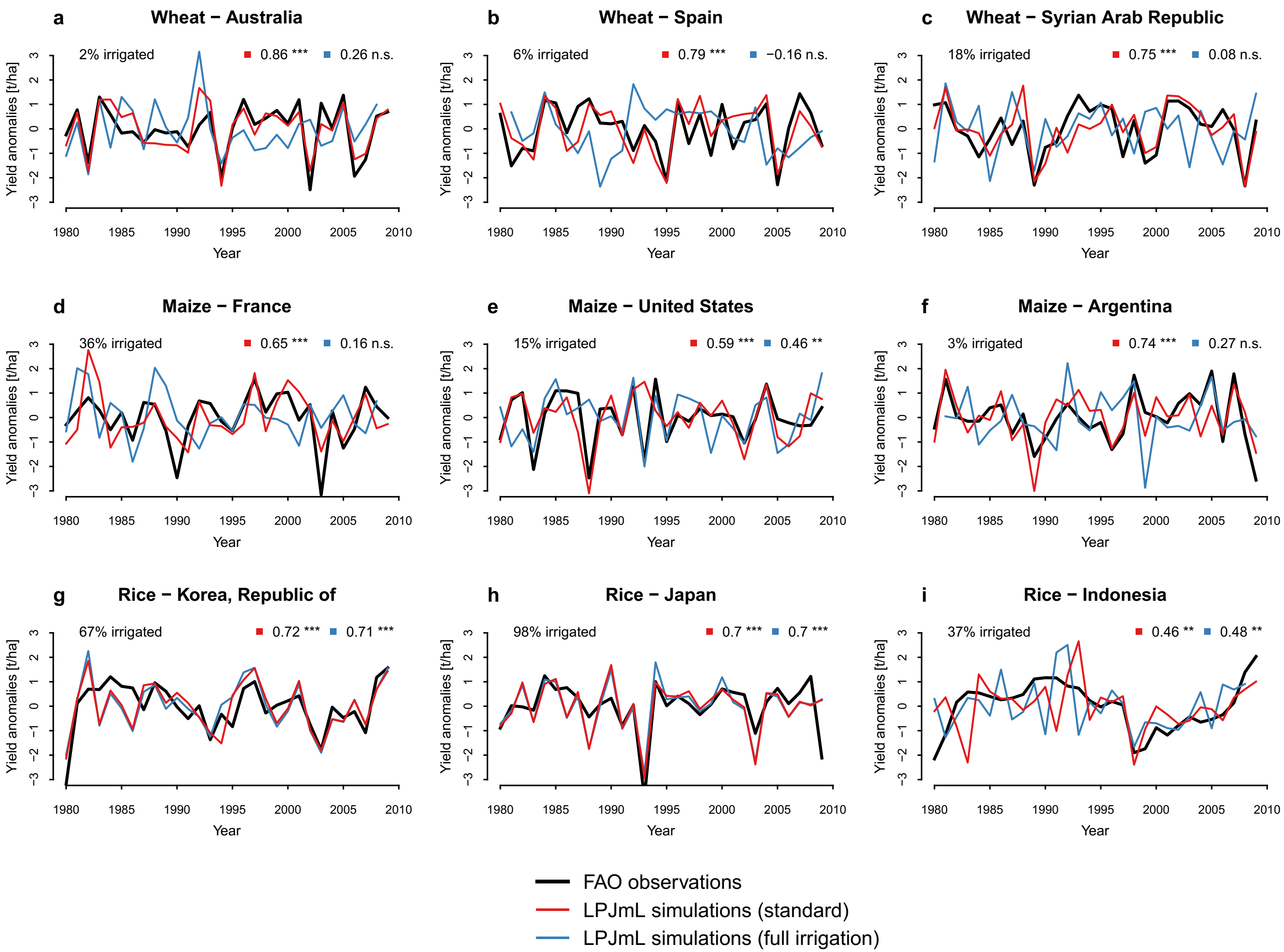


Figure B.5.: Evaluation of observed and LPJmL-simulated yield variability. Country-level time series of detrended yield anomalies from FAOstat reference data opposed to LPJmL simulations for wheat (**a**–**c**), maize (**d**–**f**), and rice (**g**–**h**). LPJmL simulations are shown for the standard simulation (in red, irrigation constrained by surface water availability) and a full-irrigation scenario (in blue, all cropland under unconstrained irrigation), i.e. water stress effects on crop growth are circumvented. Legend numbers in each figure present the Pearson's correlation coefficient (significance: $***$ for p <0.001, $**$ for p <0.05, $*$ for p <0.1, n.s. for not significant).

Appendix C.

Supplementary Information for Chapter 5

C.1. Supplementary tables and figures

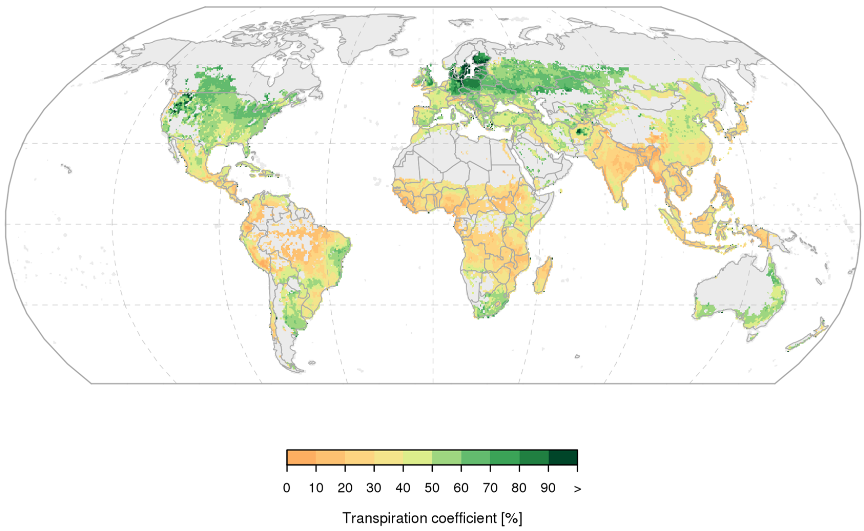


Figure C.1.: World map of transpiration coefficients. This figure illustrates spatial patterns in transpiration coefficient (transpiration per precipitation and abstracted irrigation water) averaged across rain-fed and irrigated crops during the growing seasons 1980 to 2009.

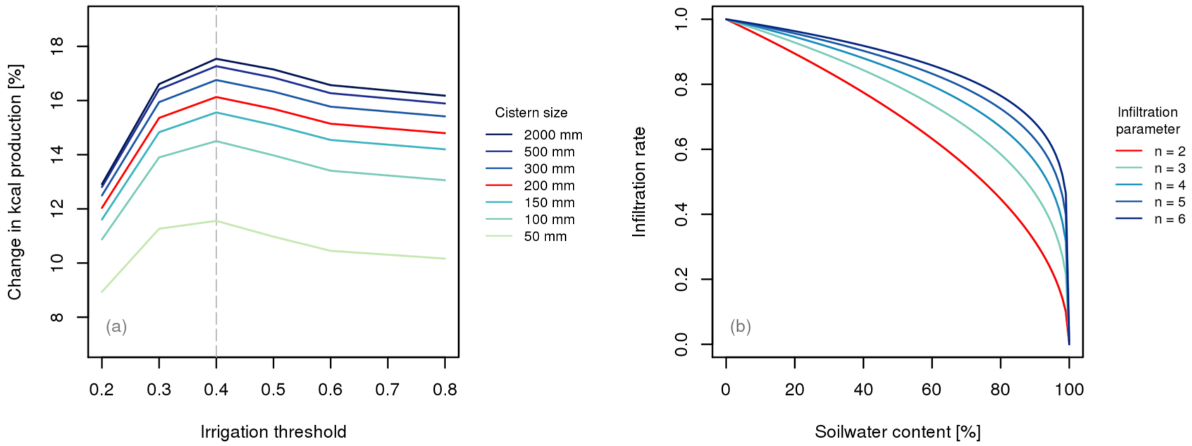


Figure C.2.: Sensitivity analysis of irrigation parameters. Sensitivity analysis for WH_{ex} parameters cistern size and irrigation threshold (**a**), and sensitivity analysis for WH_{in} infiltration parameter (p) (**b**), averaged over global rain-fed cropland for the time period 1980–2009. Default setting is $p = 2$, improved soil infiltration is realized through $p = 3, 4, 5, 6$.

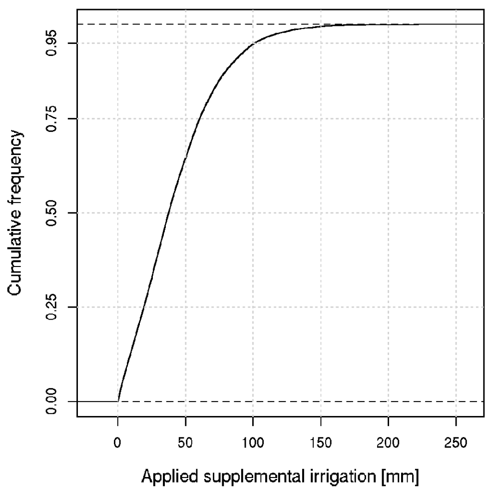


Figure C.3.: Sensitivity analysis of supplemental irrigation. Cumulative frequency distribution of applied supplemental irrigation for the "ambitious" scenario (defined in Section 5.3.1).

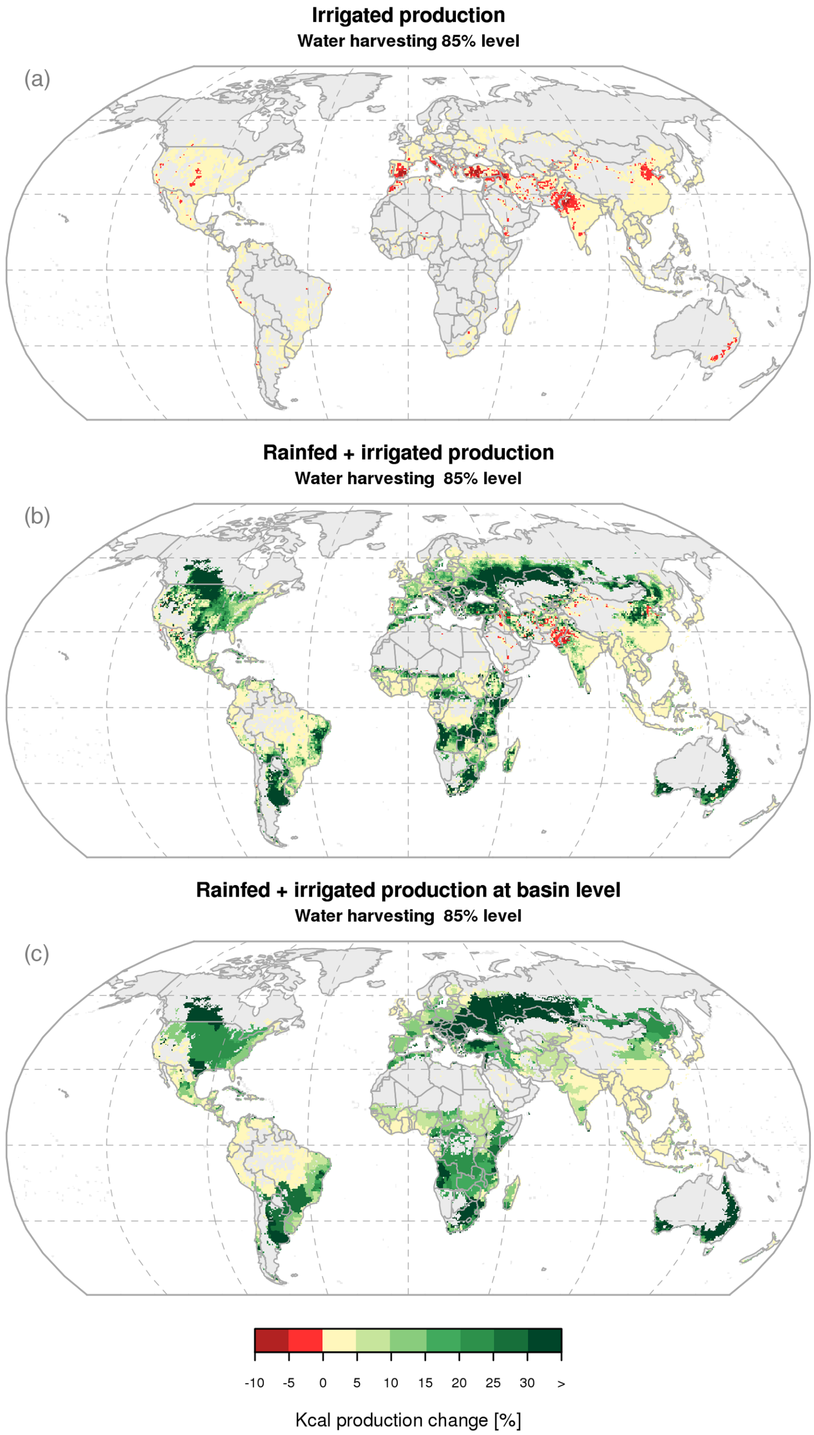


Figure C.4.: Water trade-offs associated with water harvesting. Downstream effect of water harvesting (WH_{ex} and WH_{in}) at the extreme 85% level. WH is implemented in rainfed systems only, but affects discharge for downstream users. Panel (**a**) shows the effect on irrigated kcal production, panel (**b**) on total kcal production (rainfed and irrigated) and panel (**c**) shows the change in total kcal production aggregated to the basin level.

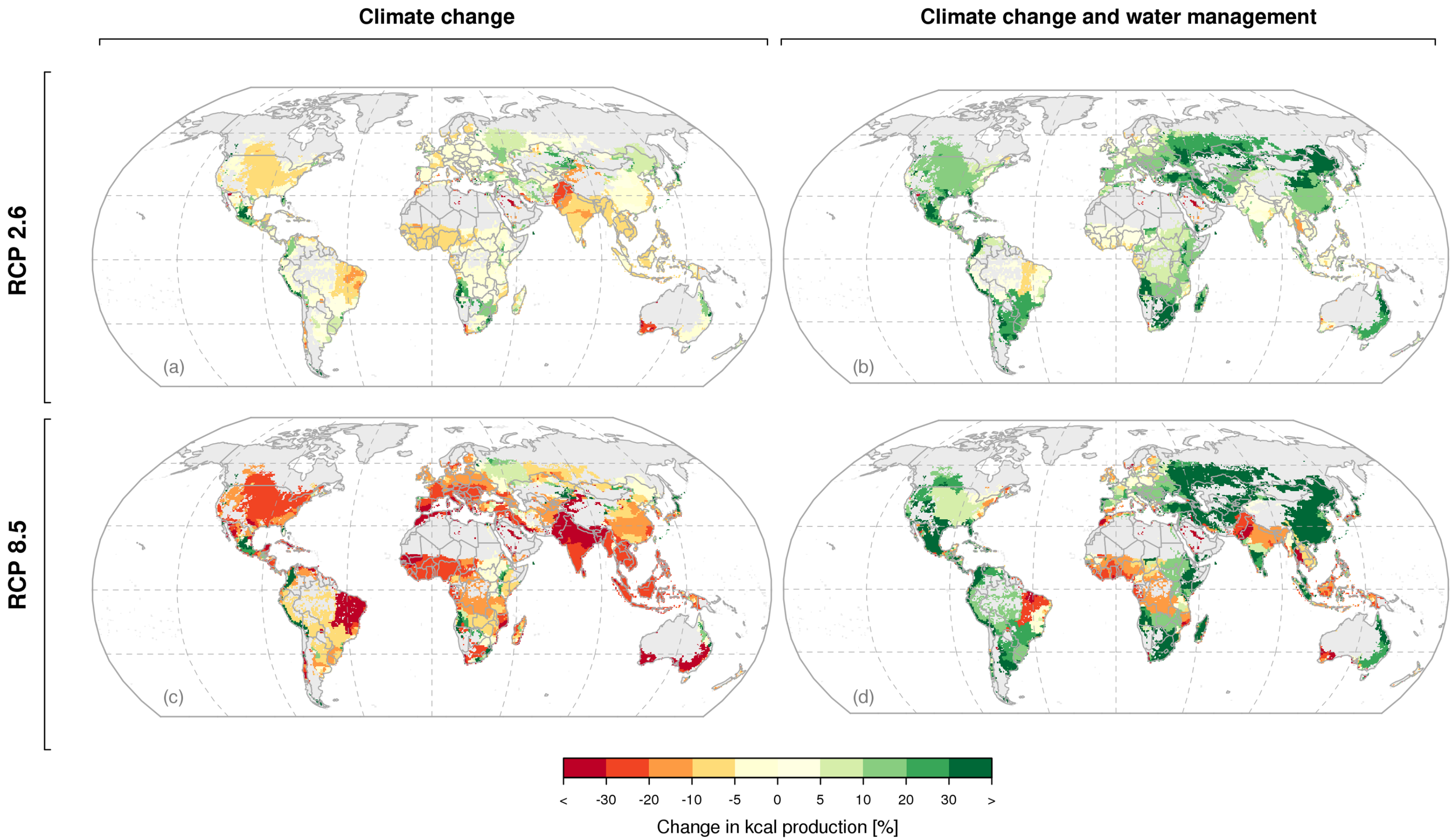


Figure C.5.: Water management buffers adverse climate change impacts — constant CO_2. Spatial patterns of potential climate change impact on global kcal prodcution under RCP 2.6 (**a**) and opposed to “low” water management (**b**); under RCP 8.5 (**c**) and opposed to “ambitious” water management (**d**), all for the time period 2070 to 2099 vs. 1980–2009 as averages across 20 GCMs and with **constant CO_2** concentration (compare Table 5.4).

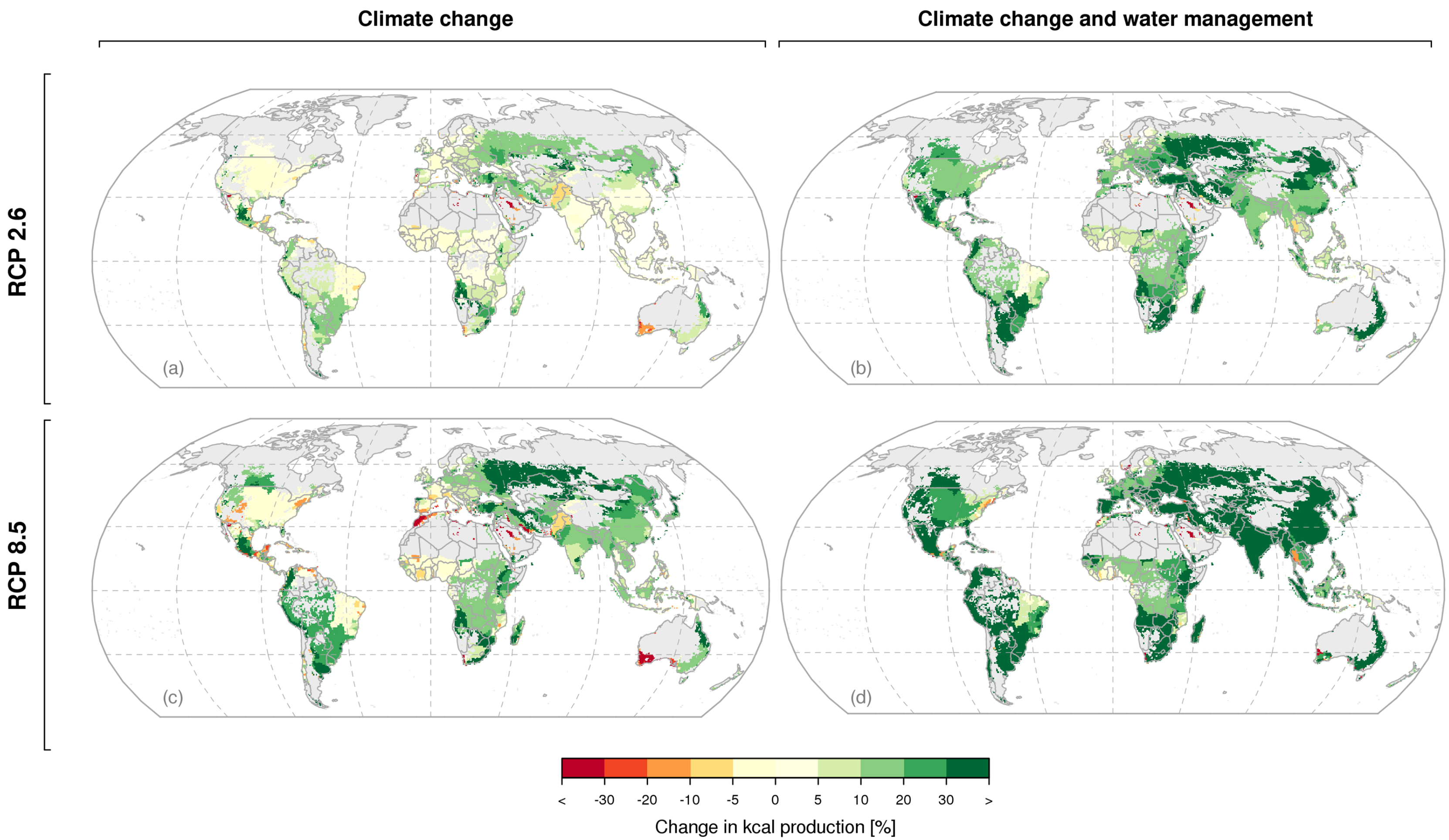


Figure C.6.: Water management buffers adverse climate change impacts — transient CO_2. Spatial patterns of potential climate change impact on global crop yields under RCP 2.6 (**a**) and opposed to "low" water management (**b**); under RCP 8.5 (**c**) and opposed to "ambitious" water management (**d**), all for the time period 2070 to 2099 vs. 1980–2009 as averages across 20 GCMs and with **transient CO_2 scenarios** concentration (compare Table 5.4).

Table C.1.: CMIP5 model and group names used in this study. Data from 20 different global climate models is used for climate change projections.

Modeling Center or Group	Institute ID	Model Name
Beijing Climate Center, China Meteorological Administration	BCC	BCC-CSM1.1 BCC-CSM1.1(m)
National Center for Atmospheric Research	NCAR	CCSM4
Community Earth System Model Contributors	NSF-DOE-NCAR	CESM1(CAM5)
Commonwealth Scientific and Industrial Research Organization in collaboration with Queensland Climate Change Centre of Excellence	CSIRO-QCCCE	CSIRO-Mk3.6.0
The First Institute of Oceanography, SOA, China	FIO	FIO-ESM
NOAA Geophysical Fluid Dynamics Laboratory	NOAA GFDL	GFDL-CM3 GFDL-ESM2G
NASA Goddard Institute for Space Studies	NASA GISS	GISS-E2-H GISS-E2-R
National Institute of Meteorological Research/Korea Meteorological Administration	NIMR/KMA	HadGEM2-AO
Met Office Hadley Centre (additional HadGEM2-ES realizations contributed by Instituto Nacional de Pesquisas Espaciais)	MOHC (additional realizations by INPE)	HadGEM2-ES
Institut Pierre-Simon Laplace	IPSL	IPSL-CM5A-LR IPSL-CM5A-MR
Japan Agency for Marine-Earth Science and Technology, Atmosphere and Ocean Research Institute (The University of Tokyo), and National Institute for Environmental Studies	MIROC	MIROC-ESM MIROC-ESM-CHEM
Atmosphere and Ocean Research Institute (The University of Tokyo), National Institute for Environmental Studies, and Japan Agency for Marine-Earth Science and Technology	MIROC	MIROC5
Meteorological Research Institute	MRI	MRI-CGCM3
Norwegian Climate Centre	NCC	NorESM1-M NorESM1-ME

Table C.2.: Selection of reference studies for water management interventions (WH_{ex}: *ex situ* water harvesting, WH_{in}: *in situ* water harvesting, SI: supplemental irrigation).

Study	Method	Region	Result
AgWater Solutions (2012)	WH_{in} and fertilizer, modeling study	sub-Saharan Africa	Potential to expand WH_{in} to 52 million ha in SSA, massive yield increases (Maize, Sorghum, Millet)
Andersson et al. (2011)	WH_{ex}, modeling study (SWAT)	South Africa	∼0% (due to high nitrogen stress, +30% with ecological sanitation)
Araya and Stroosnijder (2010)	WH_{in}, tied ridges, mulch	Ethiopia	Barley yield +44%, soil evaporation reduced by 50 to 80%
Barron et al. (1999)	WH_{ex} + SI	Kenya	$70mm$ SI increase yields by 70% on average and prevent crop failure during drought
Barron and Okwach (2005)	WH_{ex} + SI	Kenya	Maize yields +36%

Biazin et al. (2012)	WH review	sub-Saharan Africa	Micro catchments can increase soil moisture by 30%, surface runoff reduced by 60%
Bos et al. (2009)	SMC, plastic mulching	General	Yields +10 to 30%, soil evaporation reduced by 50 to 80%
	SMC, organic mulching		Soil evaporation reduced by 25% (50% soil surface covered by organic crop residues)
Botha et al. (2007)	WH_{in}	South Africa	Maize and soy yields +50% over six seasons
Bu et al. (2013)	Mulching	China	Maize yield +17 to 70% (gravel mulching) and +28 to 88% (plastic mulching)
Enfors et al. (2011)	WH_{in}, conservation tillage	Tanzania	Maize yield +17 to 41%
Fox and Rockström (2000)	WH_{ex} + SI	Burkina Faso	Sorghum grain yield +41% (+181% SI + fertilizer)
Fox and Rockström (2003)	WH_{ex} + SI	Burkina Faso	Sorghum grain yield +56% (+208% SI + fertilizer)
Hensley et al. (2000)	WH_{ex} + SI, conservation tillage	South Africa	Maize and Sunflower yields +50%
Kahinda et al. (2007)	WH_{ex} + SI, case study and modeling (APSIM)	Zimbabwe	Yield gap reduced by 53% ($kgha^{-1}$)
Kronen (1994)	Conservation tillage (tied-furrow)	Zimbabwe	Cotton, sorghum, maize yields +42, 21, and 25%, respect. over 7 seasons
Lebel et al. (2015)	WH_{ex} + SI, modeling study	sub-Saharan Africa	Maize yields +9 to 39%, water gap bridged by up to 40%
Liu et al. (2014)	SMC, plastic mulching	China, nationwide	Yields +20 to 35% (grain) +20 to 60% (cash crop), plastic film mulching in China reached ca. 20 million ha
Ngigi et al. (2005)	WH_{ex} + SI	Kenya	50 m^3 farm pond and drip irrigation prevent crop failure; adequate for supplemental irrigation 300–600 m^2
Oweis (1997)	WH_{ex} + SI	Syria	Wheat yields +28% to 356%
Oweis and Hachum (2006)	WH_{ex} + SI	Syria	Wheat yields +176% on average over three seasons
Pretty et al. (2006)	Various conservation agriculture interventions	57 countries	Average yield increases by 79%
Rockström et al. (2009a)	Conservation farming (zero tillage, water harvesting, fertilizer)	Ethiopia, Kenya, Tanzania, Zambia	Maize and Tef yields +20 to 200%
Rost et al. (2009)	WH_{ex} + SI, WH_{in}, modeling study	Global	Global crop NPP +27 to 82% (different scenarios)
Sauer et al. (1996)	Residue mulching	US	Maize yield +34 to 50%
Sivannapan (1992)	SI	southern India	Yield (various crops) +70 to 120%
Somme et al. (2004)	WH_{in}	Syria	Shrub survival rate increased by +70 to 90%
Tsubo and Walker (2007)	WH_{ex} + SI, modeling study	South Africa	Maize yields +12 to 62%
Welderufael et al. (2008)	Conservation tillage	Ethiopia	Maize yield +25 to 35%
Zhu and Yuanhong (2006)	WH_{ex} + SI	China, large-scale study	Crop yields +20 to 88%, +40% on average
Walker et al. (2005)	WH_{ex} + SI, WH_{in}, modeling study	South Africa	Maize yields +50%
Wisser et al. (2010)	WH_{ex} + SI, modeling study	Global	Cereal production +35% (medium scenario)

Bibliography

2030 Water Resources Group. 2013. *Managing Water Use in Scarce Environments - A Catalogue of Case Studies.* Technical report. Washington, D.C.: The Water Resources Group.

Acreman, M. C., and M. J. Dunbar. 2004. "Defining environmental river flow requirements – a review." *Hydrology and Earth System Sciences* 8 (5): 861–876. doi:10.5194/hess-8-861-2004.

Acreman, M. C., and A. J. D. Ferguson. 2010. "Environmental flows and the European Water Framework Directive." *Freshwater Biology* 55 (1): 32–48. doi:10.1111/j.1365-2427.2009.02181.x.

AgWater Solutions. 2012. *Regional Analysis of in situ Water Harvesting - Potential for Expansion in Sub-Saharan Africa.* Technical report July. Colombo, Sri Lanka: International Water Management Institute (IWMI), International Food Policy Research Institute (IFPRI).

Ainsworth, E. A., C. Beier, C. Calfapietra, R. Ceulemans, M. Durand-Tardif, G. D. Farquhar, D. L. Godbold, G. R. Hendrey, T. Hickler, J. Kaduk, D. F. Karnosky, B. A. Kimball, C. Körner, M. Koornneef, T. Lafarge, A. D. B. Leakey, K. F. Lewin, S. P. Long, R. Manderscheid, D. L. McNeil, T. A. Mies, F. Miglietta, J. A. Morgan, J. Nagy, R. J. Norby, R. M. Norton, K. E. Percy, A. Rogers, J.-F. Soussana, M. Stitt, H.-J. Weigel, and J. W. White. 2008. "Next generation of elevated [CO2] experiments with crops: a critical investment for feeding the future world." *Plant, cell & environment* 31 (9): 1317–24. doi:10.1111/j.1365-3040.2008.01841.x.

Alcamo, J., M. Flörke, and M. Märker. 2007. "Future long-term changes in global water resources driven by socio-economic and climatic changes." *Hydrological Sciences Journal* 52 (2): 247–275. doi:10.1623/hysj.52.2.247.

Alexandratos, N., and J. Bruinsma. 2012. *World agriculture towards 2030/2050: the 2012 revision.* Technical report 12. Rome, Italy: Food and Agriculture Organization of the United Nations (FAO).

Aligica, P. D. 2009. "Julian Simon and the "Limits to Growth" Neo-Malthusianism." *The Electronic Journal of Sustainable Development* 1 (3): 73–84.

Amthor, J. S. 1995. "Terrestrial Higher-Plant Response to Increasing Atmospheric [CO2] in Relation to the Global Carbon-Cycle." *Global Change Biology* 1 (4): 243–274. doi:10.1111/j.1365-2486.1995.tb00025.x.

Andersson, J. C., A. J. Zehnder, J. Rockström, and H. Yang. 2011. "Potential impacts of water harvesting and ecological sanitation on crop yield, evaporation and river flow regimes in the Thukela River basin, South Africa." *Agricultural Water Management* 98 (7): 1113–1124. doi:10.1016/j.agwat.2011.02.004.

Annan, K. 2003. "A Challenge to the World's Scientists." *Science* 299 (5612): 1485–1485. doi:10.1126/science.299.5612.1485.

Araya, A., and L. Stroosnijder. 2010. “Effects of tied ridges and mulch on barley (Hordeum vulgare) rainwater use efficiency and production in Northern Ethiopia.” *Agricultural Water Management* 97 (6): 841–847. doi:10.1016/j.agwat.2010.01.012.

Arthington, A. H., S. E. Bunn, N. L. Poff, and R. J. Naiman. 2006. “The Challenge of Providing Environmental Flow Rules To Sustain River Ecosystems.” *Ecological Applications* 16 (4): 1311–1318. doi:10.1890/1051-0761(2006)016.

Barnosky, A. D., N. Matzke, S. Tomiya, G. O. U. Wogan, B. Swartz, T. B. Quental, C. Marshall, J. L. Mcguire, E. L. Lindsey, K. C. Maguire, B. Mersey, and E. A. Ferrer. 2011. “Has the Earth’ s sixth mass extinction already arrived?” *Nature* 470 (7336): 51–57. doi:10.1038/nature09678.

Barron, J., E. Kemp-Benedict, J. Morris, A. de Bruin, G. Wang, and A. Fencl. 2015. “Mapping the potential success of agricultural water management interventions for smallholders: Where are the best opportunities?” *Water Resources and Rural Development* 6:24–49. doi:10.1016/j.wrr.2015.06.001.

Barron, J., J. Rockström, and F. Gichuki. 1999. “Rainwater management for dry spell mitigation in semi-arid Kenya.” *East African Agriculture and Forestry Journal* 65 (1): 57–69.

Barron, J., and G. Okwach. 2005. “Run-off water harvesting for dry spell mitigation in maize (Zea mays L.): Results from on-farm research in semi-arid Kenya.” *Agricultural Water Management* 74 (1): 1–21. doi:10.1016/j.agwat.2004.11.002.

Barron, J., J. Rockström, F. Gichuki, and N. Hatibu. 2003. “Dry spell analysis and maize yields for two semi-arid locations in east Africa.” *Agricultural and Forest Meteorology* 117 (1-2): 23–37. doi:10.1016/S0168-1923(03)00037-6.

Belder, P., D. Rohrbach, S. Twomlow, and A. Senzanje. 2007. *Can drip irrigation improve the livelihoods of smallholders? Lessons learned from Zimbabwe.* Technical report Report No. 33. Bulawayo, Zimbabwe: International Crops Research Institute for the Semi-Arid Tropics.

Beringer, T., W. Lucht, and S. Schaphoff. 2011. “Bioenergy production potential of global biomass plantations under environmental and agricultural constraints.” *GCB Bioenergy* 3 (4): 299–312. doi:10.1111/j.1757-1707.2010.01088.x.

Bhaduri, A., J. Bogardi, A. Siddiqi, H. Voigt, C. Vörösmarty, C. Pahl-Wostl, S. E. Bunn, P. Shrivastava, R. Lawford, S. Foster, H. Kremer, F. G. Renaud, A. Bruns, and V. R. Osuna. 2016. “Achieving Sustainable Development Goals from a Water Perspective.” *Frontiers in Environmental Science* 4 (October): 1–13. doi:10.3389/fenvs.2016.00064.

Biazin, B., G. Sterk, M. Temesgen, A. Abdulkedir, and L. Stroosnijder. 2012. “Rainwater harvesting and management in rainfed agricultural systems in sub-Saharan Africa - A review.” *Physics and Chemistry of the Earth, Parts A/B/C* 47-48:139–151. doi:10.1016/j.pce.2011.08.015.

Biemans, H., I. Haddeland, P. Kabat, F. Ludwig, R. W. a. Hutjes, J. Heinke, W. von Bloh, and D. Gerten. 2011. “Impact of reservoirs on river discharge and irrigation water supply during the 20th century.” *Water Resources Research* 47 (3): 1–15. doi:10.1029/2009WR008929.

Biermann, F., K. Abbott, S. Andresen, K. Backstrand, S. Bernstein, M. M. Betsill, H. Bulkeley, B. Cashore, J. Clapp, C. Folke, A. Gupta, J. Gupta, P. M. Haas, A. Jordan, N. Kanie, T. Kluvankova-Oravska, L. Lebel, D. Liverman, J. Meadowcroft, R. B. Mitchell, P. Newell, S. Oberthur, L. Olsson, P. Pattberg, R. Sanchez-Rodriguez, H. Schroeder, A. Underdal, S. C. Vieira, C. Vogel, O. R. Young, A. Brock, and R. Zondervan. 2012. "Navigating the Anthropocene: Improving Earth System Governance." *Science* 335 (6074): 1306–1307. doi:10.1126/science.1217255.

Billen, G., L. Lassaletta, and J. Garnier. 2015. "A vast range of opportunities for feeding the world in 2050: trade-off between diet, N contamination and international trade." *Environmental Research Letters* 10 (2): 025001. doi:10.1088/1748-9326/10/2/025001.

Blanco-Gutierrez, I., C. Varela-Ortega, and D. R. Purkey. 2013. "Integrated assessment of policy interventions for promoting sustainable irrigation in semi-arid environments: A hydro-economic modeling approach." *Journal of Environmental Management* 128:144–160. doi:10.1016/j.jenvman.2013.04.037.

Bogardi, J. J., B. M. Fekete, and C. J. Vörösmarty. 2013. "Planetary boundaries revisited: a view through the 'water lens'." *Current Opinion in Environmental Sustainability* 5 (6): 581–589. doi:10.1016/j.cosust.2013.10.006.

Bondeau, A., P. C. Smith, S. Zaehle, S. Schaphoff, W. Lucht, W. Cramer, D. Gerten, H. Lotze-Campen, C. Müller, M. Reichstein, and B. Smith. 2007. "Modelling the role of agriculture for the 20th century global terrestrial carbon balance." *Global Change Biology* 13 (3): 679–706. doi:10.1111/j.1365-2486.2006.01305.x.

Bonsch, M., A. Popp, A. Biewald, S. Rolinski, C. Schmitz, I. Weindl, M. Stevanovic, K. Högner, J. Heinke, S. Ostberg, J. P. Dietrich, B. Bodirsky, H. Lotze-Campen, and F. Humpenöder. 2015. "Environmental flow provision: Implications for agricultural water and land-use at the global scale." *Global Environmental Change* 30:113–132. doi:10.1016/j.gloenvcha.2014.10.015.

Bos, M., R. Kselik, R. Allen, and D. Molden. 2009. *Water Requirements for Irrigation and the Environment.* New York, NY, USA: Springer.

Bos, M., and J. Nugteren. 1990. *On irrigation efficiencies. 4th edition.* Technical report. Wageningen, Netherlands: International Institute for Land Reclamation and Improvement.

Botha, J. J., J. J. Anderson, D. C. Groenewald, N. N. Nhlabatsi, T. B. Zere, N. Mdibe, and M. N. Baiphethi. 2007. *On-farm application of in-field rainwater harvesting techniques on small plots in the Central Region of South Africa, Volume 1 of 2: main report.* Technical report. Private Bag, Gezina: Water Research Commission.

Brauman, K. A., S. Siebert, and J. A. Foley. 2013. "Improvements in crop water productivity increase water sustainability and food security - a global analysis." *Environmental Research Letters* 8 (2): 024030. doi:10.1088/1748-9326/8/2/024030.

Brisbane Declaration. 2007. *The Brisbane Declaration: environmental flows are essential for freshwater ecosystem health and human well-being.* Technical report. Brisbane: 10th International River Symposium, 3-6 September 2007.

Brouwer, C., K. Prins, and M. Heibloem. 1989. *Irrigation Water Management : Irrigation Scheduling. Training manual no. 4.* Technical report 4. Rome, Italy: FAO Land and Water Development Division.

Brouwer, C., K. Prins, M. Kay, and M. Heibloem. 1988. *Irrigation Water Management : Irrigation Methods. Training manual no. 5.* Technical report 5. FAO.

Brundtland Commission. 1987. *Report of the World Commission on Environment and Development: Our Common Future.* Technical report. Oslo: United Nations' United Nations' World Commission on Environment and Development. doi:10.1088/1751-8113/44/8/085201.

Bu, L. D., J. L. Liu, L. Zhu, S. S. Luo, X. P. Chen, S. Q. Li, R. Lee Hill, and Y. Zhao. 2013. "The effects of mulching on maize growth, yield and water use in a semi-arid region." *Agricultural Water Management* 123:71–78. doi:10.1016/j.agwat.2013.03.015.

Burney, J. A., and R. L. Naylor. 2012. "Smallholder Irrigation as a Poverty Alleviation Tool in Sub-Saharan Africa." *World Development* 40 (1): 110–123. doi:10.1016/j.worlddev.2011.05.007.

Burney, J. A., R. L. Naylor, and S. L. Postel. 2013. "The case for distributed irrigation as a development priority in sub-Saharan Africa." *Proceedings of the National Academy of Sciences of the United States of America* 110 (31): 12513–12517. doi:10.1073/pnas.1203597110.

Burt, C. M., A. J. Clemmens, T. S. Strelkoff, K. H. Solomon, R. D. Bliesner, L. A. Hardy, T. A. Howell, and D. E. Eisenhauer. 1997. "Irrigation Performance Measures: Efficiency and Uniformity." *Journal of Irrigation and Drainage Engineering* 123 (6): 423–442. doi:10.1061/(ASCE)0733-9437(1997)123:6(423).

Calderón, F., J. Oppenheimer, N. Stern, and E. Al. 2014. *Better growth, better climate - the new climate economy report - The synthesis report.* Technical report. Washington, DC: The Global Commission on the Economy and Climate.

Carr, J. A., D. A. Seekell, and P. D'Odorico. 2015. "Inequality or injustice in water use for food?" *Environmental Research Letters* 10 (2): 024013. doi:10.1088/1748-9326/10/2/024013.

Cassidy, E. S., P. C. West, J. S. Gerber, and J. A. Foley. 2013. "Redefining agricultural yields: from tonnes to people nourished per hectare." *Environmental Research Letters* 8 (3): 034015. doi:10.1088/1748-9326/8/3/034015.

Cassman, K. G., and P. Grassini. 2013. "Can there be a green revolution in Sub-Saharan Africa without large expansion of irrigated crop production?" *Global Food Security* 2 (3): 203–209. doi:10.1016/j.gfs.2013.08.004.

Chaturvedi, V., M. Hejazi, J. Edmonds, L. Clarke, P. Kyle, E. Davies, and M. Wise. 2015. "Climate mitigation policy implications for global irrigation water demand." *Mitigation and Adaptation Strategies for Global Change* 20 (3): 389–407. doi:10.1007/s11027-013-9497-4.

Chen, X., Z. Cui, M. Fan, P. Vitousek, M. Zhao, W. Ma, Z. Wang, W. Zhang, X. Yan, J. Yang, X. Deng, Q. Gao, Q. Zhang, S. Guo, J. Ren, S. Li, Y. Ye, Z. Wang, J. Huang, Q. Tang, Y. Sun, X. Peng, J. Zhang, M. He, Y. Zhu, J. Xue, G. Wang, L. Wu, N. An, L. Wu, L. Ma, W. Zhang, and F. Zhang. 2014. "Producing more grain with lower environmental costs." *Nature* 514 (7523): 486–489. doi:10.1038/nature13609.

Christian-Smith, J., H. Cooley, and P. H. Gleick. 2012. “Potential water savings associated with agricultural water efficiency improvements: A case study of California, USA.” *Water Policy* 14:194–213. doi:10.2166/wp.2011.017.

Cisneros, J., T. Oki, N. Arnell, G. Benito, J. Cogley, P. Döll, T. Jiang, and S. Mwakalila. 2014. “Freshwater Resources.” Chap. 3 in *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change,* edited by C. Field, V. Barros, D. Dokken, K. Mach, M. Mastrandrea, T. Bilir, M. Chatterjee, K. Ebi, Y. Estrada, R. Genova, B. Girma, E. Kissel, A. Levy, S. MacCracken, P. Mastrandrea, and L. White, 229–269. Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press.

Comas, J., D. Connor, M. E. M. Isselmou, L. Mateos, and H. Gómez-Macpherson. 2012. “Why has small-scale irrigation not responded to expectations with traditional subsistence farmers along the Senegal River in Mauritania?” *Agricultural Systems* 110:152–161. doi:10.1016/j.agsy.2012.04.002.

Conway, G. 1999. *The Doubly Green Revolution - Food for All in the Twenty-First Century.* 360. Ithaca, United States: Cornell University Press.

Cook, E. R., R. Seager, M. A. Cane, and D. W. Stahle. 2007. “North American drought: Reconstructions, causes, and consequences.” *Earth-Science Reviews* 81 (1-2): 93–134. doi:10.1016/j.earscirev.2006.12.002.

Cooley, H., J. Christian-smith, P. H. Gleick, L. Allen, and M. Cohen. 2008. *More with Less: Agricultural Water Conservation and Efficiency in California - A Special Focus on the Delta.* Technical report. Oakland: Pacific Institute.

Costanza, R., R. de Groot, P. Sutton, S. van der Ploeg, S. J. Anderson, I. Kubiszewski, S. Farber, and R. K. Turner. 2014. “Changes in the global value of ecosystem services.” *Global Environmental Change* 26 (1): 152–158. doi:10.1016/j.gloenvcha.2014.04.002.

Crutzen, P. J. 2002. “Geology of mankind.” *Nature* 415 (6867): 23–23. doi:10.1038/415023a.

Curran, D., and M. Fröling. 2010. “Large-scale mortality shocks and the Great Irish Famine 1845–1852.” *Economic Modelling* 27 (5): 1302–1314. doi:10.1016/j.econmod.2010.01.016.

Daamen, C. C., L. P. Simmonds, and M. V. Sivakumar. 1995. “The impact of sparse millet crops on evaporation from soil in semi-arid Niger.” *Agricultural Water Management* 27 (3-4): 225–242. doi:10.1016/0378-3774(95)01157-E.

De Fries, R. S., F. S. Chapin, J. Syvitski, R. S. DeFries, F. S. Chapin, and J. Syvitski. 2012. “Planetary Opportunities: A Social Contract for Global Change Science to Contribute to a Sustainable Future.” *BioScience* 62 (6): 603–606. doi:10.1525/bio.2012.62.6.11.

DeFries, R., J. Fanzo, R. Remans, C. Palm, S. Wood, and T. L. Anderman. 2015. “Metrics for land-scarce agriculture.” *Science* 349 (6245): 238–240. doi:10.1126/science.aaa5766.

DeFries, R. 2014. *The Big Ratchet: How humanity Thrives in the Face of Natural Crisis.* 384. Basic Books.

Deng, X.-P., L. Shan, and H. Zhang. 2006. "Improving agricultural water use efficiency in arid and semiarid areas of China." *Agricultural Water Management* 80 (1): 23–40. doi:10.1016/j.agwat.2005.07.021.

Descheemaeker, K., S. J. Oosting, S. Homann-Kee Tui, P. Masikati, G. N. Falconnier, and K. E. Giller. 2016. "Climate change adaptation and mitigation in smallholder crop–livestock systems in sub-Saharan Africa: a call for integrated impact assessments." *Regional Environmental Change.* doi:10.1007/s10113-016-0957-8.

Diamond, J. 2002. "Evolution, consequences and future of plant and animal domestication." *Nature* 418 (6898): 700–707. doi:10.1038/nature01019.

Dile, Y. T., L. Karlberg, M. Temesgen, and J. Rockström. 2013. "The role of water harvesting to achieve sustainable agricultural intensification and resilience against water related shocks in sub-Saharan Africa." *Agriculture, Ecosystems & Environment* 181:69–79. doi:10.1016/j.agee.2013.09.014.

Dillon, A. 2011. "The Effect of Irrigation on Poverty Reduction, Asset Accumulation, and Informal Insurance: Evidence from Northern Mali." *World Development* 39 (12): 2165–2175. doi:10.1016/j.worlddev.2011.04.006.

Dobermann, A., and R. Nelson. 2015. *GSDR 2015 Brief: Transformative changes of agriculture and food systems.* Technical report. United Nations.

D'Odorico, P., and M. C. Rulli. 2013. "The fourth food revolution" [in en]. *Nature Geoscience* 6 (6): 417–418. doi:10.1038/ngeo1842.

Döll, P., H. Hoffmann-Dobrev, F. Portmann, S. Siebert, A. Eicker, M. Rodell, G. Strassberg, and B. Scanlon. 2012. "Impact of water withdrawals from groundwater and surface water on continental water storage variations." *Journal of Geodynamics* 59-60:143–156. doi:10.1016/j.jog.2011.05.001.

Döll, P., H. Müller Schmied, C. Schuh, F. T. Portmann, and A. Eicker. 2014. "Global-scale assessment of groundwater depletion and related groundwater abstractions: Combining hydrological modeling with information from well observations and GRACE satellites." *Water Resources Research* 50 (7): 5698–5720. doi:10.1002/2014WR015595.

Döll, P., and S. Siebert. 2002. "Global modeling of irrigation water requirements." *Water Resources Research* 38 (4): 8–1–8–10. doi:10.1029/2001WR000355.

Douglas, E. M., S. Wood, K. Sebastian, C. J. Vörösmarty, K. M. Chomitz, and T. P. Tomich. 2006. "Policy implications of a pan-tropic assessment of the simultaneous hydrological and biodiversity impacts of deforestation." *Water Resources Management* 21 (1): 211–232. doi:10.1007/s11269-006-9050-2.

ECOSOC. 2016a. *Progress towards the Sustainable Development Goals Report of the Secretary-General Summary.* Technical report July. United Nations Economic and Social Council. doi:10.1017/S0020818300006640.

ECOSOC. 2016b. *Report of the Inter-Agency and Expert Group on Sustainable Development Goal Indicators.* Technical report March. United Nations Economic and Social Council.

Eddleston, M., L. Karalliedde, N. Buckley, R. Fernando, G. Hutchinson, G. Isbister, F. Konradsen, D. Murray, J. C. Piola, N. Senanayake, R. Sheriff, S. Singh, S. B. Siwach, and L. Smit. 2002. “Pesticide poisoning in the developing world - A minimum pesticides list.” *Lancet* 360 (9340): 1163–1167. doi:10.1016/S0140-6736(02)11204-9.

Ehrlich, P. 1968. *The Population Bomb.* 201. Sierra Club / Ballantine Books.

Elliott, J., C. Müller, D. Deryng, J. Chryssanthacopoulos, K. J. Boote, M. Büchner, I. Foster, M. Glotter, J. Heinke, T. Iizumi, R. C. Izaurralde, N. D. Mueller, D. K. Ray, C. Rosenzweig, a. C. Ruane, and J. Sheffield. 2015. “The Global Gridded Crop Model intercomparison: data and modeling protocols for Phase 1 (v1.0).” *Geoscientific Model Development Discussions* 8 (4): 261–277. doi:10.5194/gmd-8-261-2015.

Elliott, J., D. Deryng, C. Müller, K. Frieler, M. Konzmann, D. Gerten, M. Glotter, M. Flörke, Y. Wada, N. Best, S. Eisner, B. M. Fekete, C. Folberth, I. Foster, S. N. Gosling, I. Haddeland, N. Khabarov, F. Ludwig, Y. Masaki, S. Olin, C. Rosenzweig, A. C. Ruane, Y. Satoh, E. Schmid, T. Stacke, Q. Tang, and D. Wisser. 2014. “Constraints and potentials of future irrigation water availability on agricultural production under climate change.” *Proceedings of the National Academy of Sciences of the United States of America* 111 (9): 3239–44. doi:10.1073/pnas.1222474110.

Ellis, E. C. 2011. “Anthropogenic transformation of the terrestrial biosphere.” *Phil. Trans. R. Soc. A* 369:1010–1035. doi:10.1098/rsta.2010.0331.

Ellis, E. C., K. K. Goldewijk, S. Siebert, D. Lightman, and N. Ramankutty. 2010. “Anthropogenic transformation of the biomes, 1700 to 2000.” *Global Ecology and Biogeography* 19 (5): 589–606. doi:10.1111/j.1466-8238.2010.00540.x.

Enfors, E., J. Barron, H. Makurira, J. Rockström, and S. Tumbo. 2011. “Yield and soil system changes from conservation tillage in dryland farming: A case study from North Eastern Tanzania.” *Agricultural Water Management* 98 (11): 1687–1695. doi:10.1016/j.agwat.2010.02.013.

Ent, R. J. van der, H. H. G. Savenije, B. Schaefli, and S. C. Steele-Dunne. 2010. “Origin and fate of atmospheric moisture over continents.” *Water Resources Research* 46 (9): 1–12. doi:10.1029/2010WR009127.

Erb, K.-H., C. Lauk, T. Kastner, A. Mayer, M. C. Theurl, and H. Haberl. 2016. “Exploring the biophysical option space for feeding the world without deforestation.” *Nature Communications* 7 (7): 11382. doi:10.1038/ncomms11382.

European Comission. 2015. *Ecological flows in the implementation of the Water Framework Directive.* Technical report 31. European Commission. doi:10.2779/775712.

Evers, M. 2015. *MDG Lessons for post-2015 - Background paper: Lessons from implementation of water related issues of MDG 7A, 7B and 7C.* Technical report. Lueneburg, Germany: United Nations World Economic and Social Survey.

Fader, M., D. Gerten, M. Krause, W. Lucht, and W. Cramer. 2013. “Spatial decoupling of agricultural production and consumption: quantifying dependences of countries on food imports due to domestic land and water constraints.” *Environmental Research Letters* 8 (1): 014046. doi:10.1088/1748-9326/8/1/014046.

Fader, M., S. Rost, C. Müller, A. Bondeau, and D. Gerten. 2010. "Virtual water content of temperate cereals and maize: Present and potential future patterns." *Journal of Hydrology* 384 (3-4): 218–231. doi:10.1016/j.jhydrol.2009.12.011.

Falkenmark, M., A. Berntell, A. Jägerskog, J. Lundqvist, M. Matz, and H. Tropp. 2007. *On the Verge of a New Water Scarcity: A Call for Good Governance and Human Ingenuity.* Technical report. SIWI Policy Brief. Stockholm International Water Institute (SIWI).

Falkenmark, M., J. Rockström, and L. Karlberg. 2009. "Present and future water requirements for feeding humanity." *Food Security* 1 (1): 59–69. doi:10.1007/s12571-008-0003-x.

Falkenmark, M. 1998. "Dilemma when entering 21st century—rapid change but lack of sense of urgency." *Water Policy* 1 (4): 421–436.

Falkenmark, M., P. Fox, G. Persson, and J. Rockström. 2001. *Water Harvesting for Upgrading of Rainfed Agriculture.* Technical report. Stockholm, Sweden: Stockholm International Water Institute.

Falkenmark, M., and M. Lannerstad. 2010. "Food security in water-short countries – Coping with carrying capacity overshoot." In *Re-thinking Water and Food Security: Fourth Botin Foundation Water Workshop,* edited by L. Martinez-Cortina, A. Garrido, and E. Lopez-Gunn.

Falkenmark, M., J. Rockström, and H. Savenije. 2004. *Balancing water for humans and nature: the new approach in ecohydrology.* 272. London: Earthscan.

FAO. 2002. *World agriculture: towards 2015 / 2030 - Summary Report.* Technical report. Rome, Italy: Food and Agricultural Organization of the United Nations (FAO).

FAO. 2005. *Irrigation in Africa in figures AQUASTAT Survey.* Technical report. Rome, Italy: Food and Agriculture Organization of the United Nations.

FAO. 2011. *The State of the World's Land and Water Resources for Food and Agriculture - Managing systems at risk.* Technical report. Rome, Italy: Food and Agriculture Organization of the United Nations (FAO).

FAO. 2012. *FAOstat, Food and Agricultural Organization, Rome.* Food and Agricultural Organization, Rome, Italy. Accessed June 18, 2016.

FAO. 2014a. *Adapting to climate change through land and water management in Eastern Africa: Results of pilot projects in Ethiopia, Kenya and Tanzania.* Technical report. Rome, Italy: Food and Agriculture Organization of the United Nations (FAO).

FAO. 2014b. *AQUASTAT database - Food and Agriculture Organization of the United Nations (FAO).* Accessed October 18, 2014.

FAO. 2014c. *Building a common vision for sustainable food and agriculture: Principles and Approaches.* Technical report. Rome: Food and Agriculture Organization of the United Nations (FAO). doi:10.1177/109821408300400423.

FAO. 2016. *Food and agriculture - Key to achieving the 2030 Agenda for Sustainable Development.* Technical report. Rome, Italy: Food and Agricultural Organization of the United Nations.

FAO, IFAD, and WFP. 2015. *The State of Food Insecurity in the World 2015. Meeting the 2015 international hunger targets: taking stock of uneven progress.* Technical report. Rome: FAO. doi:I4646E/1/05.15.

Farquhar, G. D., S. V. Caemmerer, and J. A. Berry. 1980. "A Biochemical Model of Photosynthetic CO 2 Assimilation in Leaves of C 3 Species." *Planta* 90:78–90. doi:10.1007/BF00386231.

Faurès, J.-M., M. Svendsen, and H. Turral. 2007. "Reinventing irrigation." Chap. 9 in *Water for food, water for life: A comprehensive assessment of water management in agriculture.* Edited by D. Molden, 353–394. London: London: Earthscan, / Colombo: International Water Management Institute.

Fischer, G., F. Nachtergaele, S. Prieler, E. Teixeira, G. Tóth, H. van Velthuizen, L. Verelst, and D. Wiberg. 2012. *Global Agro-ecological Zones (GAEZ v3.0).* Technical report. IIASA, Laxenburg, Austria and FAO, Rome, Italy: IIASA/FAO.

Fischer, G., F. N. Tubiello, H. van Velthuizen, and D. A. Wiberg. 2007. "Climate change impacts on irrigation water requirements: Effects of mitigation, 1990–2080." *Technological Forecasting and Social Change* 74 (7): 1083–1107. doi:10.1016/j.techfore.2006.05.021.

Fishman, R., N. Devineni, and S. Raman. 2015. "Can improved agricultural water use efficiency save India's groundwater?" *Environmental Research Letters* 10 (8): 084022. doi:10.1088/1748-9326/10/8/084022.

Flörke, M., E. Kynast, I. Bärlund, S. Eisner, F. Wimmer, and J. Alcamo. 2013. "Domestic and industrial water uses of the past 60 years as a mirror of socio-economic development: A global simulation study." *Global Environmental Change* 23 (1): 144–156. doi:10.1016/j.gloenvcha.2012.10.018.

Foley, J., N. Ramankutty, K. A. Brauman, E. S. Cassidy, J. S. Gerber, M. Johnston, N. D. Mueller, C. O'Connell, D. K. Ray, P. C. West, C. Balzer, E. M. Bennett, S. R. Carpenter, J. Hill, C. Monfreda, S. Polasky, J. Rockström, J. Sheehan, S. Siebert, D. Tilman, and D. P. M. Zaks. 2011. "Solutions for a cultivated planet." *Nature* 478 (7369): 337–342. doi:10.1038/nature10452.

Foley, J. A., R. Defries, G. P. Asner, C. Barford, G. Bonan, S. R. Carpenter, F. S. Chapin, M. T. Coe, G. C. Daily, H. K. Gibbs, J. H. Helkowski, T. Holloway, E. A. Howard, C. J. Kucharik, C. Monfreda, J. A. Patz, I. C. Prentice, N. Ramankutty, and P. K. Snyder. 2005. "Global consequences of land use." *Science (New York, N.Y.)* 309 (5734): 570–4. doi:10.1126/science.1111772.

Folke, C. 2013. "Respecting planetary boundaries and reconnecting to the biosphere." In *Is Sustainability Still Possible? State of the World Report 2013,* 19–28. Washington: Island Press.

Folke, C., S. R. Carpenter, B. Walker, M. Scheffer, T. Chapin, and J. Rockström. 2010. "Resilience thinking: Integrating resilience, adaptability and transformability." *Ecology and Society* 15 (4). doi:10.1038/nnano.2011.191. arXiv: arXiv:1011.1669v3.

Foresight. 2011. *The Future of Food and Farming: Challenges and choices for global sustainaility.* Technical report. London: The Government Office for Science.

Fox, P., and J. Rockström. 2003. “Supplemental irrigation for dry-spell mitigation of rainfed agriculture in the Sahel.” *Agricultural Water Management* 61 (1): 29–50. doi:10.1016/S0378-3774(03)00008-8.

Fox, P., J. Rockström, and J. Barron. 2005. “Risk analysis and economic viability of water harvesting for supplemental irrigation in semi-arid Burkina Faso and Kenya.” *Agricultural Systems* 83 (3): 231–250. doi:10.1016/j.agsy.2004.04.002.

Fox, P., and J. Rockström. 2000. “Water-Harvesting for Supplementary Irrigation of Cereal Crops to Overcome Intra-Seasonal Dry-Spells in the Sahel.” *Physics and Chemistry of the Earth (B)* 25 (3): 289–296.

Fraiture, C. de, and D. Wichelns. 2010. “Satisfying future water demands for agriculture.” *Agricultural Water Management* 97 (4): 502–511. doi:10.1016/j.agwat.2009.08.008.

Frederiksen, H. D., and R. G. Allen. 2011. “A common basis for analysis, evaluation and comparison of offstream water uses.” *Water International* 36 (July): 266–282. doi:10.1080/02508060.2011.580449.

Frederiksen, H. 2011. “Correspondence, Responses to Gleick et al. (2011), which was itself a response to Frederiksen and Allen (2011).” *Water International* 37 (2): 183–197.

Galaz, V. 2012. “Environment: Planetary boundaries concept is valuable.” *Nature* 486 (7402): 191–191. doi:10.1038/486191c.

Galloway, J., and E. Cowling. 2002. “Reactive nitrogen and the world: 200 years of change.” *Ambio: A Journal of the Human Environment* 31 (2): 64–71. doi:citeulike-article-id:10495517.

Garnett, T., M. C. Appleby, A. Balmford, I. J. Bateman, T. G. Benton, P. Bloomer, B. Burlingame, M. Dawkins, L. Dolan, D. Fraser, M. Herrero, I. Hoffmann, P. Smith, P. K. Thornton, C. Toulmin, S. J. Vermeulen, and H. C. J. Godfray. 2013. “Sustainable Intensification in Agriculture: Premises and Policies.” *Science* 341 (6141): 33–34. doi:10.1126/science.1234485.

Gerten, D. 2013. “A vital link: water and vegetation in the Anthropocene.” *Hydrology and Earth System Sciences* 17 (10): 3841–3852. doi:10.5194/hess-17-3841-2013.

Gerten, D., J. Heinke, H. Hoff, H. Biemans, M. Fader, and K. Waha. 2011. “Global water availability and requirements for future food production.” *Journal of Hydrometeorology:* 110531121709055. doi:10.1175/2011JHM1328.1.

Gerten, D., S. Schaphoff, U. Haberlandt, W. Lucht, and S. Sitch. 2004. “Terrestrial vegetation and water balance—hydrological evaluation of a dynamic global vegetation model.” *Journal of Hydrology* 286 (1-4): 249–270. doi:10.1016/j.jhydrol.2003.09.029.

Gerten, D., H. Hoff, J. Rockström, J. Jägermeyr, M. Kummu, and A. V. Pastor. 2013. “Towards a revised planetary boundary for consumptive freshwater use: Role of environmental flow requirements.” *Current Opinion in Environmental Sustainability* 5 (6): 551–558. doi:10.1016/j.cosust.2013.11.001.

Gerten, D., S. Rost, W. von Bloh, and W. Lucht. 2008. “Causes of change in 20th century global river discharge.” *Geophysical Research Letters* 35 (20): 1–5. doi:10.1029/2008GL035258.

Gerten, D., S. Schaphoff, and W. Lucht. 2007. “Potential future changes in water limitations of the terrestrial biosphere.” *Climatic Change* 80 (3-4): 277–299. doi:10.1007/s10584-006-9104-8.

Gleick, P. H. 2003. "Global Freshwater Resources: Soft-Path Solutions for the 21st Century." *Science* 302 (5650): 1524–1528. doi:10.1126/science.1089967.

Gleick, P. H., J. Christian-Smith, and H. Cooley. 2011. "Water-use efficiency and productivity: rethinking the basin approach." *Water International* 36 (7): 784–798. doi:10.1080/02508060.2011.631873.

Gleick, P. H., H. Cooley, M. J. Cohen, M. Morikawa, J. Morrison, and M. Palaniappan. 2009. *The World's Water 2008-2009: The Biennal Report on Freshwater Resources.* Washington, DC: Island Press.

Gleick, P. H., and M. Palaniappan. 2010. "Peak water limits to freshwater withdrawal and use." *Proceedings of the National Academy of Sciences* 107 (25): 11155–11162. doi:10.1073/pnas.1004812107.

Global Yield Gap Atlas. 2015. Accessed September 1, 2015.

Godfray, H. C. J., J. R. Beddington, I. R. Crute, L. Haddad, D. Lawrence, J. F. Muir, J. Pretty, S. Robinson, S. M. Thomas, and C. Toulmin. 2010. "Food Security: The Challenge of Feeding 9 Billion People." *Science* 327 (5967): 812–818. doi:10.1126/science.1185383.

Godfray, H. C. J., and T. Garnett. 2014. "Food security and sustainable intensification." *Philosophical transactions of the Royal Society of London. Series B, Biological sciences* 369 (1639): 1–13. doi:10.1098/rstb.2012.0273.

Goldman-Benner, R. L., S. Benitez, T. Boucher, A. Calvache, G. Daily, P. Kareiva, T. Kroeger, and A. Ramos. 2012. "Water funds and payments for ecosystem services: practice learns from theory and theory can learn from practice." *Oryx* 46 (01): 55–63. doi:doi:10.1017/S0030605311001050.

Graeub, B. E., M. J. Chappell, H. Wittman, S. Ledermann, R. B. Kerr, and B. Gemmill-Herren. 2016. "The State of Family Farms in the World." *World Development* 87 (JUNE): 1–15. doi:10.1016/j.worlddev.2015.05.012.

GRDC. 2016. *The Global Runoff Data Centre, 56068 Koblenz, Germany.*

Grigg, D. B. 1974. *The Agricultural Systems of the World: an evolutionary approach.* Cambridge: Cambridge University Press. doi:10.1017/CBO9780511665882.

Griggs, D., M. Stafford Smith, J. Rockström, M. C. Öhman, O. Gaffney, G. Glaser, N. Kanie, I. Noble, W. Steffen, and P. Shyamsundar. 2014. "An integrated framework for sustainable development goals." *Ecology and Society* 19 (4): 49. doi:10.5751/ES-07082-190449.

Griggs, D., M. Stafford-Smith, O. Gaffney, J. Rockström, M. C. Ohman, P. Shyamsundar, W. Steffen, G. Glaser, N. Kanie, and I. Noble. 2013. "Sustainable development goals for people and planet." *Nature* 495 (7441): 305–7. doi:10.1038/495305a.

Haddeland, I., D. B. Clark, W. Franssen, F. Ludwig, F. Voß, N. W. Arnell, N. Bertrand, M. Best, S. Folwell, D. Gerten, S. Gomes, S. N. Gosling, S. Hagemann, N. Hanasaki, R. Harding, J. Heinke, P. Kabat, S. Koirala, T. Oki, J. Polcher, T. Stacke, P. Viterbo, G. P. Weedon, and P. Yeh. 2011. "Multimodel Estimate of the Global Terrestrial Water Balance: Setup and First Results." *Journal of Hydrometeorology* 12 (5): 869–884. doi:10.1175/2011JHM1324.1.

Haddeland, I., T. Skaugen, and D. P. Lettenmaier. 2006. "Anthropogenic impacts on continental surface water fluxes." *Geophysical Research Letters* 33 (8): L08406. doi:10.1029/2006GL026047.

Halsema, G. E. van, and L. Vincent. 2012. "Efficiency and productivity terms for water management: A matter of contextual relativism versus general absolutism." *Agricultural Water Management* 108:9–15. doi:10.1016/j.agwat.2011.05.016.

Hanasaki, N., S. Kanae, T. Oki, K. Masuda, K. Motoya, N. Shirakawa, Y. Shen, and K. Tanaka. 2008. "An integrated model for the assessment of global water resources – Part 2: Applications and assessments." *Hydrology and Earth System Sciences* 12 (4): 1027–1037. doi:10.5194/hess-12-1027-2008.

Hanasaki, N., T. Inuzuka, S. Kanae, and T. Oki. 2010. "An estimation of global virtual water flow and sources of water withdrawal for major crops and livestock products using a global hydrological model." *Journal of Hydrology* 384 (3-4): 232–244. doi:10.1016/j.jhydrol.2009.09.028.

Harris, I., P. D. Jones, T. J. Osborn, and D. H. Lister. 2014. "Updated high-resolution grids of monthly climatic observations - the CRU TS3.10 Dataset." *International Journal of Climatology* 34:623–642. doi:10.1002/joc.3711.

Hartmann, D. J., A. M. G. Klein Tank, M. Rusticucci, L. V. Alexander, S. Brönnimann, Y. A. R. Charabi, F. J. Dentener, E. J. Dlugokencky, D. R. Easterling, A. Kaplan, B. J. Soden, P. W. Thorne, M. Wild, and P. Zhai. 2013. *Observations: Atmosphere and Surface.* Technical report. doi:10.1017/CBO9781107415324.008.

Haxeltine, A., and I. C. Prentice. 1996. "BIOME3: An equilibrium terrestrial biosphere model based on ecophysiological constraints, resource availabilty, and competition among plant functinal types." *Global Biogeochemical Cycles* 10 (4): 693–709.

Hayashi, A., K. Akimoto, T. Tomoda, and M. Kii. 2013. "Global evaluation of the effects of agriculture and water management adaptations on the water-stressed population." *Mitigation and Adaptation Strategies for Global Change* 18 (5): 591–618. doi:10.1007/s11027-012-9377-3.

Hazrat Ali, M., L. Teang Shui, K. Chee Yan, A. F. Eloubaidy, and K. Foong. 2000. "Modeling water balance components and irrigation efficiencies in relation to water requirements for double-cropping systems." *Agricultural Water Management* 46 (2): 167–182. doi:10.1016/S0378-3774(00)00085-8.

Heinke, J., S. Ostberg, S. Schaphoff, K. Frieler, C. Müller, D. Gerten, M. Meinshausen, and W. Lucht. 2013. "A new climate dataset for systematic assessments of climate change impacts as a function of global warming." *Geoscientific Model Development* 6 (5): 1689–1703. doi:10.5194/gmd-6-1689-2013.

Helbing, D. 2013. "Globally networked risks and how to respond." *Nature* 497 (7447): 51–9. doi:10.1038/nature12047.

Henrich, J., and R. McElreath. 2003. "The Evolution of Cultural Evolution." *Evolutionary Anthropology* 12 (3): 123–135. doi:10.1002/evan.10110.

Hensley, M., J. Botha, J. Anderson, P. Van Staden, and A. Du Toit. 2000. *Optimising rainfall use efficiency for developing farmers with limited access to irrigation water. WRC Report No. 878/1/00.* Technical report. Pretoria, South Africa: Water Research Commission.

Hermoso, V., F. Pantus, J. Olley, S. Linke, J. Mugodo, and P. Lea. 2012. “Systematic planning for river rehabilitation: Integrating multiple ecological and economic objectives in complex decisions.” *Freshwater Biology* 57 (1): 1–9. doi:10.1111/j.1365-2427.2011.02693.x.

Hillel, D. 2008. “40 years of drip irrigation - reviewing the past, prospects for the future.” *Crops & Soils* 41 (4): 38–42.

Hoekstra, A. Y. 2011. “The Global Dimension of Water Governance: Why the River Basin Approach Is No Longer Sufficient and Why Cooperative Action at Global Level Is Needed.” *Water* 3 (1): 21–46. doi:10.3390/w3010021.

Hoekstra, A. Y., A. K. Chapagain, M. M. Aldaya, and M. M. Mekonnen. 2011. *The Water Footprint Assessment Manual - Setting the Global Standard.* 228. London, UK and Washington, DC, USA: Earthscan. doi:978-1-84971-279-8.

Hoekstra, A. Y., and M. M. Mekonnen. 2012. “The water footprint of humanity.” *Proceedings of the National Academy of Sciences* 109 (9): 3232–3237. doi:10.1073/pnas.1109936109. arXiv: arXiv:1408.1149.

Hoff, H., M. Falkenmark, D. Gerten, L. Gordon, L. Karlberg, and J. Rockström. 2010. “Greening the global water system.” *Journal of Hydrology* 384 (3-4): 177–186. doi:10.1016/j.jhydrol.2009.06.026.

Holling, C. S. 1973. “Resilience and Stability of Ecological Systems.” *Annual Review of Ecology and Systematics* 4:1–23.

IAASTD. 2009. *International Assessment of Agricultural Knowledge, Science and Technology for Development (Global Report).* Edited by B. McIntyre, H. Herren, J. Wakhungu, and R. Watson. Washington, DC: Island Press.

ICID. 2012. *Sprinkler and micro irrigated area - Commission on Irrigation and Drainage (ICID).*

ICID. 2016. *Agricultural Water Management for Sustainable Rural Development Annual.* Technical report. New Delhi, India: International Commission on Irrigation and Drainage Central (ICID).

ICSU, I. 2015. *Review of Targets for the Sustainable Development Goals: The Science Perspective.* Technical report. Paris: International Council for Science (ICSU).

IFPRI. 2010. *Proven Successes in Agricultural Development: A Technical Compendium to Millions Fed.* Edited by David J. Spielman and R. Pandya-Lorch. 632. Washington, D.C.: International Food Policy Research Institute. doi:10.2499/9780896296695.

IPCC. 2008. *Climate Change and Water. Technical Paper of the Intergovernmental Panel on Climate Change.* Edited by B. Bates, Z. Kundzewicz, S. Wu, and J. Palutikof. 210. Geneva: IPCC Secretariat.

IPCC. 2013. *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change,* edited by T. Stocker, D. Qin, G.-K. Plattner, M. Tignor, S. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and P. Midgley, 1535. Cambridge, United Kingdom and New York, NY, USA: Cambridge Univ Press. doi:10.1029/2000JD000115. arXiv: arXiv:1011.1669v3.

Jägermeyr, J., D. Gerten, J. Heinke, S. Schaphoff, M. Kummu, and W. Lucht. 2015. "Water savings potentials of irrigation systems: global simulation of processes and linkages." *Hydrology and Earth System Sciences* 19 (7): 3073–3091. doi:10.5194/hess-19-3073-2015.

Jägermeyr, J., D. Gerten, S. Schaphoff, J. Heinke, W. Lucht, and J. Rockström. 2016. "Integrated crop water management might sustainably halve the global food gap." *Environmental Research Letters* 11 (2): 025002. doi:10.1088/1748-9326/11/2/025002.

Jägermeyr, J., D. Gerten, W. Lucht, P. Hostert, M. Migliavacca, and R. Nemani. 2014. "A high-resolution approach to estimating ecosystem respiration at continental scales using operational satellite data." *Global Change Biology* 20 (4): 1191–1210. doi:10.1111/gcb.12443.

Jalava, M., M. Kummu, M. Porkka, S. Siebert, and O. Varis. 2014. "Diet change—a solution to reduce water use?" *Environmental Research Letters* 9 (7): 074016. doi:10.1088/1748-9326/9/7/074016.

Jensen, M. E. 2007. "Beyond irrigation efficiency." *Irrigation Science* 25 (3): 233–245. doi:10.1007/s00271-007-0060-5.

Jia, S. 2012. "More grain in the North China Plain with less water consumed: a response to Chris Perry." *Water Internationall* 37 (3): 337–340.

Kabat, P. 2013. "Water at a crossroads." *Nature Climate Change* 3 (1): 11–12. doi:10.1038/nclimate1780.

Kahinda, J. M., E. Lillie, a.E. Taigbenu, M. Taute, and R. Boroto. 2008. "Developing suitability maps for rainwater harvesting in South Africa." *Physics and Chemistry of the Earth, Parts A/B/C* 33 (8-13): 788–799. doi:10.1016/j.pce.2008.06.047.

Kahinda, J., and A. Taigbenu. 2011. "Rainwater harvesting in South Africa: Challenges and opportunities." *Physics and Chemistry of the Earth, Parts A/B/C* 36 (14-15): 968–976. doi:10.1016/j.pce.2011.08.011.

Kahinda, J., J. Rockström, A. Taigbenu, and J. Dimes. 2007. "Rainwater harvesting to enhance water productivity of rainfed agriculture in the semi-arid Zimbabwe." *Physics and Chemistry of the Earth, Parts A/B/C* 32 (15-18): 1068–1073. doi:10.1016/j.pce.2007.07.011.

Karimi, P., A. S. Qureshi, R. Bahramloo, and D. Molden. 2012. "Reducing carbon emissions through improved irrigation and groundwater management: A case study from Iran." *Agricultural Water Management* 108:52–60. doi:10.1016/j.agwat.2011.09.001.

Kastner, T., M. J. I. Rivas, W. Koch, and S. Nonhebel. 2012. "Global changes in diets and the consequences for land requirements for food." *Proceedings of the National Academy of Sciences* 109 (18): 6868–6872. doi:10.1073/pnas.1117054109.

Keller, A. A., and J. Keller. 1995. *Effective Efficiency: A Water Use Efficiency Concept for Allocating Freshwater Resources.* Technical report. Arlington, VA, USA.

Kendy, E., C. Apse, and K. Blann. 2012. *A practical guide to environmental flows for policy and planning with nine case studies in the United States.* Technical report. The Nature Conservancy.

Keys, P. W., R. J. Van Der Ent, L. J. Gordon, H. Hoff, R. Nikoli, and H. H. G. Savenije. 2012. "Analyzing precipitationsheds to understand the vulnerability of rainfall dependent regions." *Biogeosciences* 9 (2): 733–746. doi:10.5194/bg-9-733-2012.

Kijne, J., J. Barron, H. Hoff, and J. Rockström. 2009. *Opportunities to increase water productivity in agriculture with special reference to Africa and South Asia.* Technical report. Stockholm, Sweden: Stockholm Environmental Institute.

Konzmann, M., D. Gerten, and J. Heinke. 2013. "Climate impacts on global irrigation requirements under 19 GCMs, simulated with a vegetation and hydrology model." *Hydrological Sciences Journal* 58 (1): 88–105. doi:10.1080/02626667.2013.746495.

Kronen, M. 1994. "Water harvesting and conservation techniques for smallholder crop production systems." *Soil and Tillage Research* 32 (1): 71–86. doi:10.1016/0167-1987(94)90034-5.

Kummu, M., D. Gerten, J. Heinke, M. Konzmann, and O. Varis. 2014. "Climate-driven interannual variability of water scarcity in food production potential: a global analysis" [in English]. *Hydrology and Earth System Sciences* 18 (2): 447–461. doi:10.5194/hess-18-447-2014.

Kummu, M., H. de Moel, M. Porkka, S. Siebert, O. Varis, and P. J. Ward. 2012. "Lost food, wasted resources: global food supply chain losses and their impacts on freshwater, cropland, and fertiliser use." *The Science of the total environment* 438:477–89. doi:10.1016/j.scitotenv.2012.08.092.

Kummu, M., M. Fader, D. Gerten, J. Guillaume, M. Jalava, J. Jägermeyr, S. Pfister, M. Porkka, S. Siebert, and O. Varis. 2017. "Bringing it all together: ways to secure nations' food supply." *COSUST* in revisio.

Kummu, M., H. de Moel, P. J. Ward, and O. Varis. 2011. "How Close Do We Live to Water? A Global Analysis of Population Distance to Freshwater Bodies." *PLoS ONE* 6 (6): e20578. doi:10.1371/journal.pone.0020578.

Kummu, M., P. J. Ward, H. de Moel, and O. Varis. 2010. "Is physical water scarcity a new phenomenon? Global assessment of water shortage over the last two millennia." *Environmental Research Letters* 5 (3): 034006. doi:10.1088/1748-9326/5/3/034006.

Lankford, B. 2006. "Localising Irrigation Efficiency." *Irrigation and Drainage* 55:345–362. doi:10.1002/ird.

Laube, W., B. Schraven, and M. Awo. 2012. "Smallholder adaptation to climate change: Dynamics and limits in Northern Ghana." *Climatic Change* 111 (3): 753–774. doi:10.1007/s10584-011-0199-1.

Le Quesne, T., E. Kendy, and D. Weston. 2010. *The Implementation Challenge Taking stock of government policies to protect and restore environmental flows.* Technical report 2. The Nature Conservancy, WWF.

Lebel, S., L. Fleskens, P. M. Forster, L. S. Jackson, and S. Lorenz. 2015. "Evaluation of In Situ Rainwater Harvesting as an Adaptation Strategy to Climate Change for Maize Production in Rainfed Africa." *Water Resources Management* 29 (13): 4803–4816. doi:10.1007/s11269-015-1091-y.

Lenton, T. M., H. Held, E. Kriegler, J. W. Hall, W. Lucht, S. Rahmstorf, and H. J. Schellnhuber. 2008. "Tipping elements in the Earth's climate system." *Proceedings of the National Academy of Sciences* 105 (6): 1786–1793. doi:10.1073/pnas.0705414105.

Lewis, S. L. 2012. "We must set planetary boundaries wisely." *Nature* 485 (7399): 417–417. doi:10.1038/485417a.

Licker, R., M. Johnston, J. a. Foley, C. Barford, C. J. Kucharik, C. Monfreda, and N. Ramankutty. 2010. “Mind the gap: how do climate and agricultural management explain the ’yield gap’ of croplands around the world?” *Global Ecology and Biogeography* 19 (6): 769–782. doi:10.1111/j.1466-8238.2010.00563.x.

Liniger, H., R. M. Studer, C. Hauert, and M. Gurtner. 2011. *Sustainable Land Management in Practice.* Technical report. FAO.

Liu, E. K., W. Q. He, and C. R. Yan. 2014. “’White revolution’ to ’white pollution’ - agricultural plastic film mulch in China.” *Environmental Research Letters* 9 (9): 091001. doi:10.1088/1748-9326/9/9/091001.

Liu, J., C. Zang, S. Tian, J. Liu, H. Yang, S. Jia, L. You, B. Liu, and M. Zhang. 2013. “Water conservancy projects in China: Achievements, challenges and way forward.” *Global Environmental Change* 23 (3): 633–643. doi:10.1016/j.gloenvcha.2013.02.002.

Lobell, D. B., M. B. Burke, C. Tebaldi, M. D. Mastrandrea, W. P. Falcon, and R. L. Naylor. 2008. “Prioritizing Climate Change Adaptation Needs for Food Security in 2030.” *Science* 319 (5863): 607–610. doi:10.1126/science.1152339.

Loos, J., D. J. Abson, M. J. Chappell, J. Hanspach, F. Mikulcak, M. Tichit, and J. Fischer. 2014. “Putting meaning back into ”sustainable intensification”.” *Frontiers in Ecology and the Environment* 12 (6): 356–361. doi:10.1890/130157.

Luquet, D., A. Vidal, M. Smith, and J. Dauzat. 2005. “’More crop per drop’: How to make it acceptable for farmers?” *Agricultural Water Management* 76:108–119. doi:10.1016/j.agwat.2005.01.011.

MacDonald, G. K., P. D’Odorico, and D. A. Seekell. 2016. “Pathways to sustainable intensification through crop water management.” *Environmental Research Letters* 11 (9): 091001. doi:10.1088/1748-9326/11/9/091001.

Mahdi, S. S., B. S. Dhekale, S. R. Choudhury, S. A. Bangroo, and S. K. Gupta. 2015. “On the climate risks in crop production and management in India: A review.” *Australian Journal of Crop Science* 9 (7): 585–595.

Malthus, T. 1798. *An Essay on the Principle of Population - As it Affects the Future Improvement of Society, with Remarks on the Speculations of Mr Godwin, M. Condorcet, and Other Writers.* 126. London, UK: J. Johnson.

Mati, B., T. De Bock, M. Malesu, E. Khaka, A. Oduor, M. Nyabenge, and V. Oduor. 2007. *Mapping the Potential of Rainwater Harvesting Technologies in Africa: A GIS overview on development domains for the continent and ten selected countries.* Technical report 6. Nairobi, Kenya: World Agroforestry Centre (ICRAF)), Netherlands Ministry of Foreign Affairs.

Matson, P. a. 1997. “Agricultural Intensification and Ecosystem Properties.” *Science* 277 (5325): 504–509. doi:10.1126/science.277.5325.504.

Matthews, R. B., M. Rivington, S. Muhammed, A. C. Newton, and P. D. Hallett. 2012. “Adapting crops and cropping systems to future climates to ensure food security: The role of crop modelling.” *Global Food Security:* 1–5. doi:10.1016/j.gfs.2012.11.009.

Mauser, W., G. Klepper, F. Zabel, R. Delzeit, T. Hank, B. Putzenlechner, and A. Calzadilla. 2015. "Global biomass production potentials exceed expected future demand without the need for cropland expansion." *Nature Communications* 6:8946. doi:10.1038/ncomms9946.

Maxton, G., and J. Randers. 2016. *Reinventing Prosperity. Managing Economic Growth to Reduce Unemployment, Inequality and Climate Change.* 240. Greystone Books.

Mazvimavi, K., S. Twomlow, P. Belder, and L. Hove. 2008. *An assessment of the sustainable uptake of conservation farming in Zimbabwe. Global Theme on Agroecosystems Report no. 39.* Technical report. Bulawayo, Zimbabwe: International Crops Research Institute for the Semi-Arid Tropics.

Meadows, D. H., D. L. Meadows, J. Randers, and W. Behrens III. 1972. *The limits to growth,* 210. New York: Universe Books.

Mekonnen, M. M., and A. Y. Hoekstra. 2011. "The green, blue and grey water footprint of crops and derived crop products." *Hydrology and Earth System Sciences* 15 (5): 1577–1600. doi:10.5194/hess-15-1577-2011.

Merrey, D. J., and H. Sally. 2008. "Micro-agricultural water management technologies for food security in southern Africa: part of the solution or a red herring?" *Water Policy* 10 (5): 515. doi:10.2166/wp.2008.025.

Meyers, J., C. Baird, and R. Choate. 1970. *Evaporation losses in sprinkler irrigation.* Technical report 1968. Gainesville, FL, USA: Florida Water Resources Research Center.

Molden, D., ed. 2007. *Water for Food, Water for Life: A Comprehensive Assessment of Water Management in Agriculture.* London: London: Earthscan, / Colombo: International Water Management Institute.

Molden, D., T. Oweis, P. Steduto, P. Bindraban, M. a. Hanjra, and J. Kijne. 2010. "Improving agricultural water productivity: Between optimism and caution." *Agricultural Water Management* 97 (4): 528–535. doi:10.1016/j.agwat.2009.03.023.

Molina, M. J. 2009. "Planetary boundaries: Identifying abrupt change." *Nature Reports Climate Change* 3 (0910): 115–116. doi:10.1038/climate.2009.96.

Molle, F., and J. Berkoff, eds. 2007. *Irrigation water pricing: the gap between theory and practice.* Oxfordshire, UK: CAB International. doi:10.1079/9781845932923.0000.

Monastersky, R. 2015. "The Human Age." *Nature* 519 (7542): 144–147. doi:10.1038/519144a.

Ki-moon, B. 2008. "The New Face Of Hunger." *The Washington Post* (Washigton, D.C.), no. March 12.

Mueller, N. D., J. S. Gerber, M. Johnston, D. K. Ray, N. Ramankutty, and J. A. Foley. 2012. "Closing yield gaps through nutrient and water management." *Nature* 490 (7419): 254–7. doi:10.1038/nature11420.

Müller Schmied, H., L. Adam, S. Eisner, G. Fink, M. Florke, H. Kim, T. Oki, F. Theodor Portmann, R. Reinecke, C. Riedel, Q. Song, J. Zhang, and P. Doll. 2016. "Variations of global and continental water balance components as impacted by climate forcing uncertainty and human water use." *Hydrology and Earth System Sciences* 20 (7): 2877–2898. doi:10.5194/hess-20-2877-2016.

Munia, H., J. H. A. Guillaume, N. Mirumachi, M. Porkka, Y. Wada, and M. Kummu. 2016. "Water stress in global transboundary river basins: significance of upstream water use on downstream stress." *Environmental Research Letters* 11 (1): 014002. doi:10.1088/1748-9326/11/1/014002.

Naiman, R. J., S. E. Bunn, C. Nilsson, G. E. Petts, G. Pinay, and L. C. Thompson. 2002. "Legitimizing fluvial ecosystems as users of water: An overview." *Environmental Management* 30 (4): 455–467. doi:10.1007/s00267-002-2734-3.

Nelson, G. C., M. W. Rosegrant, A. Palazzo, I. Gray, C. Ingersoll, R. Robertson, S. Tokgoz, and T. Zhu. 2010. *Food Security, Farming, and Climate Change to 2050: scenarios, results, policy.* Technical report. Washington, D.C.: International Food Policy Research Institute.

Neumann, K., E. Stehfest, P. H. Verburg, S. Siebert, C. Müller, and T. Veldkamp. 2011. "Exploring global irrigation patterns: A multilevel modelling approach." *Agricultural Systems* 104 (9): 703–713. doi:10.1016/j.agsy.2011.08.004.

Ngigi, S. N. 2003. "What is the limit of up-scaling rainwater harvesting in a river basin?" *Physics and Chemistry of the Earth, Parts A/B/C* 28 (20-27): 943–956. doi:10.1016/j.pce.2003.08.015.

Ngigi, S. N., H. H. Savenije, J. N. Thome, J. Rockström, and F. P. de Vries. 2005. "Agro-hydrological evaluation of on-farm rainwater storage systems for supplemental irrigation in Laikipia district, Kenya." *Agricultural Water Management* 73 (1): 21–41. doi:10.1016/j.agwat.2004.09.021.

Nicol, A., S. Langan, M. Victor, and J. Gonsalves. 2015. *Water-smart agriculture in East Africa.* 1:1–30. Colombo, Sri Lanka: "International Water Management Institute (IWMI). CGIAR Research Program on Water, Land / Ecosystems (WLE); Global Water Initiative East Africa (GWI EA). doi:10.5337/2015.203. arXiv: arXiv:1011.1669v3.

Nordhaus, B. Y. T. E. D., M. Shellenberger, and L. Blomqvist. 2012. *The Planetary Boundaries Hypothesis - Review of the Evidence.* Technical report June. Breakthrough Institute.

Oweis, T. 1997. *Supplemental Irrigation: A Highly Efficient Water-Use Practice.* Technical report October. Aleppo, Syria: International Center for Agricultural Research in the Dry Areas.

Oweis, T. Y., and A. Y. Hachum. 2003. "Improving Water Productivity in the Dry Areas of West Asia and North Africa." Chap. 11 in *Water Productivity in Agriculture: Limits and Opportunities for Improvement,* edited by J. Kijne, R. Barker, and D. Molden, 179–198. Wallingford, UK: CAB International.

Oweis, T., and A. Hachum. 2006. "Water harvesting and supplemental irrigation for improved water productivity of dry farming systems in West Asia and North Africa." *Agricultural Water Management* 80 (1-3): 57–73. doi:10.1016/j.agwat.2005.07.004.

Pahl-Wostl, C., A. Arthington, J. Bogardi, S. E. Bunn, H. Hoff, L. Lebel, E. Nikitina, M. Palmer, L. R. N. Poff, K. Richards, M. Schlüter, R. Schulze, A. St-Hilaire, R. Tharme, K. Tockner, and D. Tsegai. 2013a. "Environmental flows and water governance: Managing sustainable water uses." *Current Opinion in Environmental Sustainability* 5 (3-4): 341–351. doi:10.1016/j.cosust.2013.06.009.

Pahl-Wostl, C., C. Vörösmarty, A. Bhaduri, J. Bogardi, J. Rockström, and J. Alcamo. 2013b. "Towards a sustainable water future: Shaping the next decade of global water research." *Current Opinion in Environmental Sustainability* 5 (6): 708–714. doi:10.1016/j.cosust.2013.10.012.

Pastor, a. V., F. Ludwig, H. Biemans, H. Hoff, and P. Kabat. 2014. "Accounting for environmental flow requirements in global water assessments." *Hydrology and Earth System Sciences* 18 (12): 5041–5059. doi:10.5194/hess-18-5041-2014.

Perry, C. J., and P. J. G. J. Hellegers. 2012. "To what extent do improved irrigation technologies extend aquifer life?" *Hydrogeology Journal* 20:907–913. doi:10.1007/s10040-012-0872-0.

Perry, C., P. Steduto, R. G. Allen, and C. M. Burt. 2009. "Increasing productivity in irrigated agriculture: Agronomic constraints and hydrological realities." *Agricultural Water Management* 96 (11): 1517–1524. doi:10.1016/j.agwat.2009.05.005.

Petschel-Held, G., H. Schellnhuber, T. Bruckner, F. Tóth, and K. Hasselmann. 1999. "The tolerable windows approach: theoretical and methodological foundations." *Climatic Change* 41:303–331. doi:10.1023/A:1005487123751.

Pfeiffer, L., and C. Y. C. Lin. 2014. "Does efficient irrigation technology lead to reduced groundwater extraction? Empirical evidence." *Journal of Environmental Economics and Management* 67 (2): 189–208. doi:10.1016/j.jeem.2013.12.002.

Pfeiffer, L., and C. Lin. 2009. "Incentive-based groundwater conservation programs: perverse consequences?" *Agricultural and Resource Economics* 12 (6): 1–4.

Pingali, P., and M. Rosegrant. 1994. *Confronting the Environmental Consequences of the Green Revolution In Asia.* Technical report 2. Washigton, D.C.: International Food Policy Research Institute.

Pingali, P. L. 2012. "Green Revolution: Impacts, limits, and the path ahead." *Proceedings of the National Academy of Sciences* 109 (31): 12302–12308. doi:10.1073/pnas.0912953109.

Plusquellec, H. 2002. "Is the daunting challenge of irrigation achievable?" *Irrigation and Drainage* 51 (3): 185–198. doi:10.1002/ird.51.

Poff, N. L., C. M. Brown, T. E. Grantham, J. H. Matthews, M. a. Palmer, C. M. Spence, R. L. Wilby, M. Haasnoot, G. F. Mendoza, K. C. Dominique, and A. Baeza. 2015. "Sustainable water management under future uncertainty with eco-engineering decision scaling." *Nature Climate Change* 6 (1): 25–34. doi:10.1038/nclimate2765.

Poff, N. L., and J. H. Matthews. 2013. "Environmental flows in the Anthropocence: past progress and future prospects." *Current Opinion in Environmental Sustainability* 5 (6): 667–675. doi:10.1016/j.cosust.2013.11.006.

Poff, N. L., B. D. Richter, A. H. Arthington, S. E. Bunn, R. J. Naiman, E. Kendy, M. Acreman, C. Apse, B. P. Bledsoe, M. C. Freeman, J. Henriksen, R. B. Jacobson, J. G. Kennen, D. M. Merritt, J. H. O'Keeffe, J. D. Olden, K. Rogers, R. E. Tharme, and A. Warner. 2010. "The ecological limits of hydrologic alteration (ELOHA): A new framework for developing regional environmental flow standards." *Freshwater Biology* 55 (1): 147–170. doi:10.1111/j.1365-2427.2009.02204.x.

Poff, N. L., and J. K. H. Zimmerman. 2010. "Ecological responses to altered flow regimes: A literature review to inform the science and management of environmental flows." *Freshwater Biology* 55 (1): 194–205. doi:10.1111/j.1365-2427.2009.02272.x.

Population Reference Bureau. 2016. *2016 World Population Data Sheet With a Special Focus on Human Needs.* Technical report. Washigton, D.C.: Population Reference Bureau.

Porkka, M., D. Gerten, S. Schaphoff, S. Siebert, and M. Kummu. 2016. "Causes and trends of water scarcity in food production." *Environmental Research Letters* 11 (1): 015001. doi:10.1088/1748-9326/11/1/015001.

Porter, J., L. Xie, A. Challinor, K. Cochrane, S. Howden, M. Iqbal, D. Lobell, and M. Travasso. 2014. "Food security and food production systems." Chap. 7 in *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change,* edited by C. Field, V. Barros, D. Dokken, K. Mach, M. Mastrandrea, T. Bilir, M. Chatterjee, K. Ebi, Y. Estrada, R. Genova, B. Girma, E. Kissel, A. Levy, S. MacCracken, P. Mastrandrea, and L. White, 485–533. Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press.

Portmann, F. T., S. Siebert, and P. Döll. 2010. "MIRCA2000 - Global monthly irrigated and rainfed crop areas around the year 2000: A new high-resolution data set for agricultural and hydrological modeling." *Global Biogeochemical Cycles* 24 (1): 1–24. doi:10.1029/2008GB003435.

Postel, S. 1999. *Pillar of sand.* 313. W. W. Norton & Company Ltd.

Postel, S. 2013. "Sustaining Freshwater and Its Dependents." In *State of the World 2013,* 51–62. Washington, DC: Island Press/Center for Resource Economics. doi:10.5822/978-1-61091-458-1_5.

Postel, S., P. Polak, F. Gonzales, and J. Keller. 2001. "Drip Irrigation for Small Farmers: A New Initiative to Alleviate Hunger and Poverty." *Water International* 26 (1): 3–13. doi:10.1080/02508060108686882.

Postel, S., G. Daily, and P. Ehrlich. 1996. "Human Appropriation Of Renewable Fresh Water." *Science* 271 (5250): 785–788.

Prentice, I., W. Cramer, S. Harrison, R. Leemans, R. Monserud, and A. Solomon. 1992. "A Global Biome Model Based on Plant Physiology and Dominance, Soil Properties and Climate." *Journal of Biogeography* 19 (2): 117–134.

Pretty, J. N., a. D. Noble, D. Bossio, J. Dixon, R. E. Hine, F. W. T. P. De Vries, and J. I. L. Morison. 2006. "Resource-conserving agriculture increases yields in developing countries." *Environmental Science and Technology* 40 (4): 1114–1119. doi:10.1021/es051670d.

Pretty, J., and R. Hine. 2001. *Reducing Food Poverty with Sustainable Agriculture : A Summary of New Evidence.* Technical report February 2001.

Pretty, J., C. Toulmin, and S. Williams. 2011. "Sustainable intensification in African agriculture." *International Journal of Agricultural Sustainability* 9 (1): 5–24. doi:10.3763/ijas.2010.0583.

Pugh, T., C. Müller, J. Elliott, D. Deryng, C. Folberth, S. Olin, E. Schmid, and A. Arneth. 2016. "Climate analogues suggest limited potential for intensification of production on current croplands under climate change." *Nature Communications* 7:12608. doi:10.1038/ncomms12608.

Ramsar Convention. 2015. *State of the World's Wetlands and their Services to People: A compilation of recent analyses.* Technical report June. doi:10.2139/ssrn.2589447.

Raworth, K. 2012a. “A safe and just space for humanity: Can We Live Within the Doughnut?” *Oxfam Discussion Papers.*

Raworth, K. 2012b. “Living in the doughnut.” *Nature Climate Change* 2 (4): 225–226. doi:10.1038/nclimate1457.

Ray, D. K., and J. A. Foley. 2013. “Increasing global crop harvest frequency: recent trends and future directions.” *Environmental Research Letters* 8 (4): 044041. doi:10.1088/1748-9326/8/4/044041.

Ray, D. K., N. Ramankutty, N. D. Mueller, P. C. West, and J. a. Foley. 2012. “Recent patterns of crop yield growth and stagnation.” *Nature Communications* 3:1293. doi:10.1038/ncomms2296.

Reganold, J. P., and J. M. Wachter. 2016. “Organic agriculture in the twenty-first century.” *Nature Plants* 2 (2): 15221. doi:10.1038/nplants.2015.221.

Reid, W. V., H. A. Mooney, A. Cropper, D. Capistrano, S. R. Carpenter, K. Chopra, P. Dasgupta, T. Dietz, A. K. Duraiappah, R. Hassan, R. Kasperson, R. Leemans, R. M. May, T. McMichael, P. Pingali, C. Samper, R. Scholes, R. T. Watson, A.H. Zakri, Z. Shidong, N. J. Ash, E. Bennett, P. Kumar, M. J. Lee, C. Raudsepp-Hearne, H. Simons, J. Thonell, and M. B. Zurek. 2005. *Ecosystems and human well-being: Synthesis / Millennium Ecosystem Assessment,* edited by J. Sarukhán and A. Whyte, 5:1–100. Washington, DC.: Island Press. doi:10.1196/annals.1439.003. arXiv: arXiv:1011.1669v3.

Rensburg, L. D. van, C. B. Bothma, C. H. Fraenkel, P. A. L. Le Roux, and M. Hensley. 2012. “In-Field Rainwater Harvesting: Mechanical Tillage Implements and Scope for Upscaling.” *Irrigation and Drainage* 61 (October): 138–147. doi:10.1002/ird.1682.

Reynolds, T. W., S. R. Waddington, C. L. Anderson, A. Chew, Z. True, and A. Cullen. 2015. “Environmental impacts and constraints associated with the production of major food crops in Sub-Saharan Africa and South Asia.” *Food Security* 7 (4): 795–822. doi:10.1007/s12571-015-0478-1.

Richter, B. D., M. M. Davis, C. Apse, and C. Konrad. 2012. “A Presumptive Standard For Environmental Flow Protection.” *River Research and Applications* 28 (8): 1312–1321. doi:10.1002/rra.1511.

Ringler, C., A. Bhaduri, and R. Lawford. 2013. “The nexus across water, energy, land and food (WELF): potential for improved resource use efficiency?” *Current Opinion in Environmental Sustainability* 5 (6): 617–624. doi:10.1016/j.cosust.2013.11.002.

Rockström, J., and A. Klum. 2015. *Big World, Small Planet: Abundance within Planetary Boundaries.* Stockholm: Bokförlaget Max Ström.

Rockstrom, J., M. Lannerstad, and M. Falkenmark. 2007. “Assessing the water challenge of a new green revolution in developing countries.” *Proceedings of the National Academy of Sciences* 104 (15): 6253–6260. doi:10.1073/pnas.0605739104.

Rockström, J. 2003. “Water for food and nature in drought-prone tropics: vapour shift in rain-fed agriculture.” *Philosophical transactions of the Royal Society of London. Series B, Biological sciences* 358 (1440): 1997–2009. doi:10.1098/rstb.2003.1400.

Rockström, J. 2012. *Planetary Boundaries: Addressing Some Key Misconceptions.* Accessed October 12, 2016.

Rockström, J., J. Barron, and P. Fox. 2003. "Water productivity in rain-fed agriculture: challenges and opportunities for smallholder farmers in drought-prone tropical agroecosystems." Chap. 9 in *Water Productivity in Agriculture: Limits and Opportunities for Improvement,* edited by J. Kijne, R. Barker, and D. Molden, 145–162. Wallingford, UK: CAB International.

Rockström, J., M. Falkenmark, T. Allan, C. Folke, L. Gordon, A. Jägerskog, M. Kummu, M. Lannerstad, M. Meybeck, D. Molden, S. Postel, H. H. G. Savenije, U. Svedin, A. Turton, and O. Varis. 2014. "The unfolding water drama in the Anthropocene: Towards a resilience-based perspective on water for global sustainability." *Ecohydrology* 7 (5): 1249–1261. doi:10.1002/eco.1562.

Rockström, J., and M. Falkenmark. 2000. "Semiarid Crop Production from a Hydrological Perspective: Gap between Potential and Actual Yields." *Critical Reviews in Plant Sciences* 19 (4): 319–346.

Rockström, J., and M. Falkenmark. 2015. "Agriculture: Increase water harvesting in Africa." *Nature* 519 (7543): 283–285. doi:10.1038/519283a.

Rockström, J., and L. Karlberg. 2010. "The Quadruple Squeeze: Defining the safe operating space for freshwater use to achieve a triply green revolution in the Anthropocene." *Ambio* 39 (3): 257–265. doi:10.1007/s13280-010-0033-4.

Rockström, J., P. Kaumbutho, J. Mwalley, A. Nzabi, M. Temesgen, L. Mawenya, J. Barron, J. Mutua, and S. Damgaard-Larsen. 2009a. "Conservation farming strategies in East and Southern Africa: Yields and rain water productivity from on-farm action research." *Soil and Tillage Research* 103 (1): 23–32. doi:10.1016/j.still.2008.09.013.

Rockström, J., W. Steffen, K. Noone, A. Persson, F. S. Chapin III, E. Lambin, T. M. Lenton, M. Scheffer, F. C, H.-J. Schellnhuber, B. Nykvist, C. A. de Wit, T. HUghes, S. van der Leeuw, H. Rodhe, S. Sörlin, P. K. Snyder, R. Constanza, U. Svedin, M. Falkenmark, L. Karlberg, R. W. Corell, V. J. Fabry, J. Hansen, B. Walker, D. Liverman, K. Richardson, P. Crutzen, and F. J. 2009b. "Planetary boundaries: explorint the safe operating space for humanity." *Ecology and Society* 14 (2): 1–32. doi:10.1038/461472a. arXiv: 461472a `[10.1038]`.

Rockström, J., W. Steffen, K. Noone, Å. Persson, F. S. Chapin, E. F. Lambin, T. M. Lenton, M. Scheffer, C. Folke, H. J. Schellnhuber, B. Nykvist, C. A. de Wit, T. Hughes, S. van der Leeuw, H. Rodhe, S. Sörlin, P. K. Snyder, R. Costanza, U. Svedin, M. Falkenmark, L. Karlberg, R. W. Corell, V. J. Fabry, J. Hansen, B. Walker, D. Liverman, K. Richardson, P. Crutzen, and J. A. Foley. 2009c. "A safe operating space for humanity." *Nature* 461 (7263): 472–475. doi:10.1038/461472a.

Rockström, J., J. Williams, G. Daily, A. Noble, N. Matthews, L. Gordon, H. Wetterstrand, F. DeClerck, M. Shah, P. Steduto, C. de Fraiture, N. Hatibu, O. Unver, J. Bird, L. Sibanda, and J. Smith. 2016. "Sustainable intensification of agriculture for human prosperity and global sustainability." *Ambio:* 1–14. doi:10.1007/s13280-016-0793-6.

Rogers, D., F. Lamm, M. Alam, T. Trooien, G. C. P. Barnes, and K. Mankin. 1997. *Efficiencies and water losses of irrigation systems.* Technical report. Kansas State University.

Rohwer, J., D. Gerten, and W. Lucht. 2007. *Development of functional irrigation types for improved global crop modelling.* Technical report 104. Potsdam, Germany: Potsdam Institute for Climate Impact Research.

Rosegrant, M. W., X. Cai, and S. A. Cline. 2002. *World Water and Food to 2025: Dealing with Scarcity.* Technical report. Washigton, D.C.: International Food Policy Research Institute.

Rosenzweig, C., J. Elliott, D. Deryng, A. C. Ruane, C. Müller, A. Arneth, K. J. Boote, C. Folberth, M. Glotter, N. Khabarov, K. Neumann, F. Piontek, T. a. M. Pugh, E. Schmid, E. Stehfest, H. Yang, and J. W. Jones. 2014. "Assessing agricultural risks of climate change in the 21st century in a global gridded crop model intercomparison." *Proceedings of the National Academy of Sciences* 111 (9): 3268–3273. doi:10.1073/pnas.1222463110.

Rosenzweig, M. R., and K. I. Wolpin. 1993. "Credit Market Constraints, Consumption Smoothing, and the Accumulation of Durable Production Assets in Low-Income Countries: Investments in Bullocks in India." *Journal of Political Economy* 101 (2): 223–244. doi:10.1086/261874.

Rost, S., D. Gerten, and U. Heyder. 2008a. "Human alterations of the terrestrial water cycle through land management." *Advances in Geosciences* 18:43–50. doi:10.5194/adgeo-18-43-2008.

Rost, S., D. Gerten, A. Bondeau, W. Lucht, J. Rohwer, and S. Schaphoff. 2008b. "Agricultural green and blue water consumption and its influence on the global water system." *Water Resources Research* 44 (9): 1–17. doi:10.1029/2007WR006331.

Rost, S., D. Gerten, H. Hoff, W. Lucht, M. Falkenmark, and J. Rockström. 2009. "Global potential to increase crop production through water management in rainfed agriculture." *Environmental Research Letters* 4 (4): 044002. doi:10.1088/1748-9326/4/4/044002.

Rudolf, B., A. Becker, U. Chneider, A. Meyer-Christoffer, and M. Ziese. 2010. *'GPCC Full Data Reanalysis Version 5' providing high-quality gridded monthly precipitation data for the global land-surface is public available since December.* Technical report December. GPCC Status Report.

Ruttan, V. W. 1971. "Technology and the Environment." *American Journal of Agricultural Economics* 53 (5): 707. doi:10.2307/1238069.

Sabin, P. 2013. *The Bet: Paul Ehrlich, Julian Simon, and Our Gamble over Earth's Future.* 320. Yale University Press.

Al-Said, F. A., M. Ashfaq, M. Al-Barhi, M. a. Hanjra, and I. a. Khan. 2012. "Water Productivity of Vegetables Under Modern Irrigation Methods in Oman." *Irrigation and Drainage* 61 (4): 477–489. doi:10.1002/ird.1644.

Samberg, L. H. 2016. "Food security: A collaboration worth its weight in grain." *Nature* 537 (7622): 624–625. doi:10.1038/nature19431.

Sánchez, P. A. 2010. "Tripling crop yields in tropical Africa." *Nature Geoscience* 3 (5): 299–300. doi:10.1038/ngeo853.

Sauer, T. J., J. L. Hatfield, and J. H. Prueger. 1996. "Corn Residue Age and Placement Effects on Evaporation and Soil Thermal Regime." *Soil Science Society of America Journal* 60 (5): 1558–64. doi:10.2136/sssaj1996.03615995006000050039x.

Sauer, T., P. Havlík, U. a. Schneider, E. Schmid, G. Kindermann, and M. Obersteiner. 2010. "Agriculture and resource availability in a changing world: The role of irrigation." *Water Resources Research* 46 (6): n/a–n/a. doi:10.1029/2009WR007729.

Schaphoff, S., U. Heyder, S. Ostberg, D. Gerten, J. Heinke, and W. Lucht. 2013. "Contribution of permafrost soils to the global carbon budget." *Environmental Research Letters* 8 (1): 014026. doi:10.1088/1748-9326/8/1/014026.

Schellnhuber, H. J. 1999. "'Earth system' analysis and the second Copernican revolution." *Nature* 402:C19–C23.

Schellnhuber, H. 2015. *Selbstverbrennung: Die fatale Dreiecksbeziehung zwischen Klima, Mensch und Kohlenstoff.* 784. München: C. Bertelsmann.

Schlenker, W., and D. B. Lobell. 2010. "Robust negative impacts of climate change on African agriculture." *Environmental Research Letters* 5 (1): 014010. doi:10.1088/1748-9326/5/1/014010.

Schmitz, C., H. Lotze-Campen, D. Gerten, J. P. Dietrich, B. Bodirsky, A. Biewald, and A. Popp. 2013. "Blue water scarcity and the economic impacts of future agricultural trade and demand." *Water Resources Research* 49 (6): 3601–3617. doi:10.1002/wrcr.20188.

Schneider, U., A. Becker, P. Finger, A. Meyer-Christoffer, M. Ziese, and B. Rudolf. 2014. "GPCC's new land surface precipitation climatology based on quality-controlled in situ data and its role in quantifying the global water cycle." *Theoretical and Applied Climatology* 115 (1-2): 15–40. doi:10.1007/s00704-013-0860-x.

Searchinger, T., C. Hanson, J. Ranganathan, B. Lipinski, R. Waite, R. Winterbottom, A. Dinshaw, and R. Heimlich. 2013. *Creating a Sustainable Food Future - A menu of solutions to sustainably feed more than 9 billion people by 2050.* Technical report. Washington, DC: World Resources Institute.

Seckler, D. 1996. *The New Era of Water Resources Management: From "Dry" to "Wet" Water Savings.* Technical report. Colombo, Sri Lanka: International Irrigation Management Institute (IIMI).

Seckler, D., D. Molden, and R. Sakthivadivel. 2003. "The Concept of Efficiency in Water- resources Management and Policy." Chap. 3 in *Water productivity in agriculture: limits and opportunities for improvement,* edited by J. Kijne, R. Barker, and D. Molden, 37–51. International Water Management Institute, Colombo, Sri Lanka. doi:10.2136/vzj2007.0085br.

SEI. 2005. *Sustainable Pathways to Attain the Millennium Development Goals - Assessing the Key Role of Water, Energy and Sanitation.* Technical report. Stockholm: Stockholm Environmental Institute.

Seufert, V., N. Ramankutty, and J. a. Foley. 2012. "Comparing the yields of organic and conventional agriculture." *Nature* 485 (7397): 229–32. doi:10.1038/nature11069.

Shah, T. 2014. *Groundwater governance and irrigated agriculture, TEC background papers no. 19.* Technical report 19. Stockholm, Sweden: Global Water Partnership Technical Committee.

Shiklomanov, I. A., and J. C. Rodda. 2003. *World Water Resources at the Beginning of the Twenty-First Century,* 452. Cambridge, UK.

Siebert, S., J. Burke, J. M. Faures, K. Frenken, J. Hoogeveen, P. Döll, and F. T. Portmann. 2010. "Groundwater use for irrigation – a global inventory." *Hydrology and Earth System Sciences* 14 (10): 1863–1880. doi:10.5194/hess-14-1863-2010.

Siebert, S., P. Döll, J. Hoogeveen, J.-M. Faures, K. Frenken, and S. Feick. 2005. "Development and validation of the global map of irrigation areas." *Hydrology and Earth System Sciences* 9 (4): 535–547. doi:10.5194/hessd-2-1299-2005.

Siebert, S., M. Kummu, M. Porkka, P. Döll, N. Ramankutty, and B. R. Scanlon. 2015. "A global data set of the extent of irrigated land from 1900 to 2005." *Hydrology and Earth System Sciences* 19 (19): 1521–1545. doi:10.13019/M20599.

Siebert, S., and P. Döll. 2010. "Quantifying blue and green virtual water contents in global crop production as well as potential production losses without irrigation." *Journal of Hydrology* 384 (3-4): 198–217. doi:10.1016/j.jhydrol.2009.07.031.

Siebert, S., P. Döll, S. Feick, J. Hoogeveen, and K. Frenken. 2007. *Global Map of Irrigation Areas Version 4.0.1 [CD-Rom], FAO Land and Water Digital Media Ser. 34.* Rome, FAO.

Siebert, S., and F. Ewert. 2014. "Future crop production threatened by extreme heat." *Environmental Research Letters* 9 (4): 041001. doi:10.1088/1748-9326/9/4/041001.

Simon, J. 1981. *The Ultimate Resource.* 734. Princeton University Press.

Simons, G., W. Bastiaanssen, and W. Immerzeel. 2015. "Water reuse in river basins with multiple users: A literature review." *Journal of Hydrology* 522:558–571. doi:10.1016/j.jhydrol.2015.01.016.

Sitch, S., B. Smith, I. C. Prentice, a. Arneth, a. Bondeau, W. Cramer, J. O. Kaplan, S. Levis, W. Lucht, M. T. Sykes, K. Thonicke, and S. Venevsky. 2003. "Evaluation of ecosystem dynamics, plant geography and terrestrial carbon cycling in the LPJ dynamic global vegetation model." *Global Change Biology* 9 (2): 161–185. doi:10.1046/j.1365-2486.2003.00569.x.

Sivannapan, R. 1992. *Status report on drip irrigation in India.* Technical report. New Delhi: Indian National Committee on Irrigation and Drainage.

Smakhtin, V. 2008. "Basin Closure and Environmental Flow Requirements." *International Journal of Water Resources Development* 24 (2): 227–233. doi:10.1080/07900620701723729.

Smakhtin, V., C. Revenga, and P. Döll. 2004. "A pilot global assessment of environmental water requirements and scarcity." *Water International* 29 (3): 307–317. doi:10.1080/02508060408691785.

Smil, V. 1991. "Population Growth and Nitrogen: An Exploration of a Critical Existential Link." *Population and Development Review* 17 (4): 569–601.

Somme, G., T. Y. Oweis, A. Abdulal, A. Bruggeman, and A. Ali. 2004. *Micro-catchment water harvesting for improved vegetative cover in the Syrian Badia. On-Farm Water Husbandry Series, N0.3.* Technical report. Aleppo, Syria: International Center for Agricultural Research in the Dry Areas (ICARDA).

Stacke, T., and S. Hagemann. 2012. "Development and evaluation of a global dynamical wetlands extent scheme." *Hydrology and Earth System Sciences* 16 (8): 2915–2933. doi:10.5194/hess-16-2915-2012.

Steffen, W., J. Crutzen, and J. R. McNeill. 2007. “The Anthropocene: are humans now overwhelming the great forces of Nature?” *Ambio* 36 (8): 614–21.

Steffen, W., R. Leinfelder, J. Zalasiewicz, C. N. Waters, M. Williams, A. D. Barnosky, A. Cearreta, P. Crutzen, M. Edgeworth, C. Ellis, I. J. Fairchild, A. Galuszka, J. Grinevald, A. Haywood, J. Ivar, C. Jeandel, J. R. Mcneill, E. Odada, N. Oreskes, and A. Revkin. 2016. “Stratigraphic and Earth System approaches to defining the Anthropocene Earth ' s Future.” *Earth's Future* 4:324–345. doi:10.1002/2016EF000379.

Steffen, W., K. Richardson, J. Rockstrom, S. E. Cornell, I. Fetzer, E. M. Bennett, R. Biggs, S. R. Carpenter, W. de Vries, C. a. de Wit, C. Folke, D. Gerten, J. Heinke, G. M. Mace, L. M. Persson, V. Ramanathan, B. Reyers, and S. Sorlin. 2015. “Planetary boundaries: Guiding human development on a changing planet.” *Science* 347 (6223): 1259855–1259855. doi:10.1126/science.1259855.

Stevenson, J. R., N. Villoria, D. Byerlee, T. Kelley, and M. Maredia. 2013. “Green Revolution research saved an estimated 18 to 27 million hectares from being brought into agricultural production.” *Proceedings of the National Academy of Sciences* 110 (21): 8363–8368. doi:10.1073/pnas.1208065110.

Strzepek, K., and B. Boehlert. 2010. “Competition for water for the food system.” *Philosophical Transactions of the Royal Society B: Biological Sciences* 365 (1554): 2927–2940. doi:10.1098/rstb.2010.0152.

Studer, R., and H. Linger. 2013. *Water Harvesting: Guidelines to Good Practice.* Technical report. Rome: Centre for Development and Environment (CDE), Bern; Rainwater Harvesting Implementation Network (RAIN), Amsterdam; MetaMeta, Wageningen; The International Fund for Agricultural Development (IFAD).

Taylor, K. E., R. J. Stouffer, and G. A. Meehl. 2012. *An overview of CMIP5 and the experiment design.* doi:10.1175/BAMS-D-11-00094.1. arXiv: arXiv:1011.1669v3.

Tennant, D. L. 1976. “Instream Flow Regimens for Fish, Wildlife, Recreation and Related Environmental Resources.” *Fisheries* 1:6–10.

Tessmann, S. A. 1980. *Environmental Assessment. Technical Appendix E in "Reconnaissance Elements of The Western Dakotas Region of South Dakota".* Technical report. Brookings, SD, USA: South Dakota Water Resources Institute.

The Rockefeller Foundation. 2015. *Incentive-Based Instruments for Water Management.* Technical report December. New York, NY, USA: The Rockefeller Foundation.

The Royal Society. 2009. *Reaping the benefits: science and the sustainable intensification of global agriculture,* 1–74. London, UK: The Royal Society. doi:10.2104/mbr08064.

Thomas, R. 2005. “Zooarchaeology, improvement and the British Agricultural Revolution.” *International Journal of Historical Archaeology* 9 (2): 71–88. doi:10.1007/s10761-005-8140-9.

Tibbs, H. 2011. “Changing cultural values and the transition to sustainability.” *Journal of Futures Studies* 15 (3): 13–32.

Tilman, D. 1999. "Global environmental impacts of agricultural expansion: The need for sustainable and efficient practices." *Proceedings of the National Academy of Sciences* 96 (11): 5995–6000. doi:10.1073/pnas.96.11.5995.

Tilman, D., C. Balzer, J. Hill, and B. L. Befort. 2011. "Global food demand and the sustainable intensification of agriculture." *Proceedings of the National Academy of Sciences* 108 (50): 20260–20264. doi:10.1073/pnas.1116437108.

Tilman, D., K. G. Cassman, P. A. Matson, R. Naylor, and S. Polasky. 2002. "Agricultural sustainability and intensive production practices." *Nature* 418 (6898): 671–677. doi:10.1038/nature01014.

Tony Elumelu Foundation. 2016. *Unleashing Africa' s Agricultural Entrepreneurs: Improving the Enabling Environment for Agriculture.* Technical report February. Tony Elumelu Foundation.

Tsubo, M., and S. Walker. 2007. "An assessment of productivity of maize grown under water harvesting system in a semi-arid region with special reference to ENSO." *Journal of Arid Environments* 71 (3): 299–311. doi:10.1016/j.jaridenv.2007.04.007.

UNDP. 2015. *Human Development Report 2015.* Technical report. New York, NY, USA: United Nations Development Programme (UNDP).

UNEP. 2011. *Ecosystems for water and food security,* edited by E. Boelee, 194. Nairobi, Colombo: United Nations Environment Programme, International Water Management Institute.

UNESCO. 2002. *Universal declaration on cultural diversity.* Technical report 1. Paris: United Nations Educational, Scientific and Cultural Organization (UNESCO).

UNFPA. 2013. *Population Dynamics in the Post-2015 Development Agenda - Report of the Global Thematic Consultation on Population Dynamics.* Technical report. United Nations Population Fund (UNFPA), United Nations Department of Economic and Social Affairs (UNDESA), United Nations Human Settlements Programme (UN-HABITAT), International Organization for Migration (IOM).

United Nations. 2015a. *A/70/L1 Transforming our world: the 2030 Agenda for Sustainable Development.* Technical report. New York City: United Nations.

United Nations. 2015b. *Global Sustainable Development Report - 2015 Edition.* Technical report. United Nations.

United Nations. 2015c. *World Population Prospects: The 2015 Revision.* Technical report. United Nations, Department of Economic and Social Affairs, Population Devision.

United Nations. 2016a. *United Nations webpage.* Accessed November 10, 2016.

United Nations. 2016b. *World Economic and Social Survey 2014 / 2015 - Learning from national policies supporting MDG implementation.* Technical report. New York: United Nation.

Valin, H., R. D. Sands, D. van der Mensbrugghe, G. C. Nelson, H. Ahammad, E. Blanc, B. Bodirsky, S. Fujimori, T. Hasegawa, P. Havlik, E. Heyhoe, P. Kyle, D. Mason-D'Croz, S. Paltsev, S. Rolinski, A. Tabeau, H. van Meijl, M. von Lampe, and D. Willenbockel. 2014. "The future of food demand: understanding differences in global economic models." *Agricultural Economics* 45 (1): 51–67. doi:10.1111/agec.12089.

Vickers, A. 2001. *Handbook of Water Use and Conservation.* 446. Amherst, Mass.: Waterplow Press.

Vörösmarty, C. J., A. Y. Hoekstra, S. E. Bunn, D. Conway, J. Gupta, C. J. Vörösmarty, A. Subramanian, B. Brown, A. T. Wolf, N. R. Council, J. P. M. Syvitski, C. Zarfl, A. E. Lumsdon, J. Berlekamp, L. Tydecks, K. Tockner, D. Dudgeon, W. E. Forum, A. Y. Hoekstra, M. M. Mekonnen, P. H. Gleick, M. Palaniappan, J. Gupta, C. Pahl-Wostl, R. Zondervan, UN-Water, and WHO/UNICEF. 2015. "Fresh water goes global." *Science* 349 (6247): 555–561. doi:10.1126/science.aac6009.

Vörösmarty, C. J., P. B. McIntyre, M. O. Gessner, D. Dudgeon, A. Prusevich, P. Green, S. Glidden, S. E. Bunn, C. a. Sullivan, C. R. Liermann, and P. M. Davies. 2010. "Global threats to human water security and river biodiversity." *Nature* 467 (7315): 555–561. doi:10.1038/nature09549.

Vörösmarty, C. J., C. Leveque, C. Revenga, R. Bos, C. Caudill, J. Chilton, E. M. Douglas, M. Meybeck, D. Prager, P. Balvanera, S. Barker, M. Maas, C. Nilsson, T. Oki, and C. A. Reidy. 2005. "Chapter 7: Fresh Water." Chap. 7 in *Millennium Ecosystem Assessment: Current State and Trends Assessment,* edited by J. Sarukhán and A. Whyte, 165–207. Washigton, D.C.: Island Press.

Wada, Y., L. P. H. van Beek, and M. F. P. Bierkens. 2011. "Modelling global water stress of the recent past: on the relative importance of trends in water demand and climate variability." *Hydrology and Earth System Sciences* 15 (12): 3785–3808. doi:10.5194/hess-15-3785-2011.

Wada, Y., D. Wisser, and M. F. P. Bierkens. 2014. "Global modeling of withdrawal, allocation and consumptive use of surface water and groundwater resources." *Earth System Dynamics* 5 (1): 15–40. doi:10.5194/esd-5-15-2014.

Wada, Y., L. P. H. van Beek, and M. F. P. Bierkens. 2012. "Nonsustainable groundwater sustaining irrigation: A global assessment." *Water Resources Research* 48 (November 2011): W00L06. doi:10.1029/2011WR010562.

Wada, Y., and M. F. P. Bierkens. 2014. "Sustainability of global water use: past reconstruction and future projections." *Environmental Research Letters* 9 (10): 104003. doi:10.1088/1748-9326/9/10/104003.

Wada, Y., D. Wisser, S. Eisner, M. Flörke, D. Gerten, I. Haddeland, N. Hanasaki, Y. Masaki, F. T. Portmann, T. Stacke, Z. Tessler, and J. Schewe. 2013. "Multimodel projections and uncertainties of irrigation water demand under climate change." *Geophysical Research Letters* 40 (17): 4626–4632. doi:10.1002/grl.50686.

Waha, K., L. G. J. van Bussel, C. Müller, and A. Bondeau. 2012. "Climate-driven simulation of global crop sowing dates." *Global Ecology and Biogeography* 21 (2): 247–259. doi:10.1111/j.1466-8238.2011.00678.x.

Walker, B., C. S. Holling, S. R. Carpenter, and A. Kinzig. 2004. "Resilience, Adaptability and Transformability in Social – ecological Systems." *Ecology and Society* 9 (2): 5. doi:10.1103/PhysRevLett.95.258101.

Walker, S., M. Tsubo, and M. Hensley. 2005. "Quantifying risk for water harvesting under semi-arid conditions: Part II. Crop yield simulation." *Agricultural Water Management* 76 (2): 94–107. doi:10.1016/j.agwat.2005.01.007.

Wani, S., T. Sreedevi, J. Rockström, and Y. Ramakrishna. 2009. "Rainfed Agriculture - Past Trends and Future Prospects." Chap. 1 in *Rainfed Agriculture: Unlocking the Potential,* edited by S. Wani, J. Rockström, and T. Oweis, 1–35. Wallingford, UK: CAB International.

Ward, F. a., and M. Pulido-Velazquez. 2008. "Water conservation in irrigation can increase water use." *Proceedings of the National Academy of Sciences* 105 (47): 18215–18220. doi:10.1073/pnas.0805554105.

Watanabe, S., S. Kanae, S. Seto, P. J.-F. Yeh, Y. Hirabayashi, and T. Oki. 2012. "Intercomparison of bias-correction methods for monthly temperature and precipitation simulated by multiple climate models." *Journal of Geophysical Research* 117 (D23): D23114. doi:10.1029/2012JD018192.

Weisdorf, J. L. 2005. "From Foraging To Farming: Explaining The Neolithic Revolution." *Journal of Economic Surveys* 19 (4): 561–586. doi:10.1111/j.0950-0804.2005.00259.x.

Welderufael, W. a., P. a. L. Le Roux, and M. Hensley. 2008. "Quantifying rainfall-runoff relationships on the Dera Calcic Fluvic Regosol ecotope in Ethiopia." *Agricultural Water Management* 95 (11): 1223–1232. doi:10.1016/j.agwat.2008.04.007.

Wheeler, T., and J. von Braun. 2013. "Climate Change Impacts on Global Food Security." *Science* 341 (6145): 508–513. doi:10.1126/science.1239402.

Wisser, D., S. Frolking, E. M. Douglas, B. M. Fekete, A. H. Schumann, and C. J. Vörösmarty. 2010. "The significance of local water resources captured in small reservoirs for crop production - A global-scale analysis." *Journal of Hydrology* 384 (3-4): 264–275. doi:10.1016/j.jhydrol.2009.07.032.

World Bank. 2010. *World Development Report 2010 - Development and Climate Change.* Technical report. Washington, D.C.: World Bank.

World Bank. 2013. *The Sahel: New Push to Transform Agriculture with More Support for Pastoralism and Irrigation.* Accessed August 17, 2015.

World Social Science Report. 2016. *Challenging Inequalities: Pathways to a Just World.* Technical report. Paris: ISSC, IDS and UNESCO.

World Water Assessment Programme. 2015a. *The United Nations World Water Development Report 2015: Facing the challenges. Case Studies and Indicators.* Technical report. Paris: UNESCO.

World Water Assessment Programme. 2015b. *The United Nations World Water Development Report 2015: Water for a Sustainable World.* Technical report. Paris: UNESCO. doi:10.1016/S1366-7017(02)00004-1.

Wriedt, G., M. Van der Velde, A. Aloe, and F. Bouraoui. 2009. "Estimating irrigation water requirements in Europe." *Journal of Hydrology* 373 (3-4): 527–544. doi:10.1016/j.jhydrol.2009.05.018.

Xie, H., L. You, B. Wielgosz, and C. Ringler. 2014. "Estimating the potential for expanding smallholder irrigation in Sub-Saharan Africa." *Agricultural Water Management* 131:183–193. doi:10.1016/j.agwat.2013.08.011.

You, L., C. Ringler, U. Wood-Sichra, R. Robertson, S. Wood, T. Zhu, G. Nelson, Z. Guo, and Y. Sun. 2011. "What is the irrigation potential for Africa? A combined biophysical and socioeconomic approach." *Food Policy* 36 (6): 770–782. doi:10.1016/j.foodpol.2011.09.001.

Zhang, W., G. Cao, X. Li, H. Zhang, C. Wang, Q. Liu, X. Chen, Z. Cui, J. Shen, R. Jiang, G. Mi, Y. Miao, F. Zhang, and Z. Dou. 2016. "Closing yield gaps in China by empowering smallholder farmers." *Nature* 537 (7622): 671–674. doi:10.1038/nature19368.

Zhang, Y., A. H. Arthington, S. E. Bunn, S. Mackay, J. Xia, and M. Kennard. 2012. "Classification of flow regimes for environmental flow assessment in regulated rivers: the Huai River Basin, China." *River Research and Applications* 28 (7): 989–1005. doi:10.1002/rra.1483.

Zhu, Q., and L. Yuanhong. 2006. "Rainwater harvesting: The key to sustainable rural development in Gansu, China." *Waterlines* 24 (4): 4–7. doi:10.3362/0262-8104.2006.017.

Zwart, S. J., and W. G. M. Bastiaanssen. 2004. "Review of measured crop water productivity values for irrigated wheat, rice, cotton and maize." *Agricultural Water Management* 69:115–133. doi:10.1016/j.agwat.2004.04.007.

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